THESIS

APPLICATIONS FOR THREE-DIMENSIONAL COMPUTER
GRAPHIC CLOUD REPRESENTATIONS PRODUCED
FROM SATELLITE IMAGERY

Submitted by

Arthur C. Meade

Department of Atmospheric Science

In partial fulfillment of the requirements

for the Degree of Master of Science

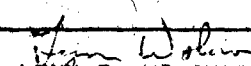Colorado State University

Fort Collins, Colorado

Spring, 1985

85 06 24 082

REPORT DOCUMENTATION PAGE

BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
AFIT/CI/NR 85-50T		

4. TITLE (and Subtitle)	5. TYPE OF REPORT & PERIOD COVERED
Applications For Three-Dimensional Computer Graphic Cloud Representations Produced From Satellite Imagery	THESIS/DISSERTATION
	6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)	8. CONTRACT OR GRANT NUMBER(s)
Arthur C. Meade	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
AFIT STUDENT AT: Colorado State University	

11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE
AFIT/NR WPAFB OH 45433	1985
	13. NUMBER OF PAGES
	101

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report)
	UNCLASS
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

APPROVED FOR PUBLIC RELEASE: IAW AFR 190-1

LYNN E. WOLAVER
Dean for Research and
Professional Development
AFIT, Wright-Patterson AFB OH

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

ATTACHED

DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE

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ENTITLED Applications for Three-Dimensional Computer Graphic Cloud

_____ Representations Produced from Satellite Imagery _____

BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF

_____ Master of Science _____

Committee on Graduate Work

_____

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Adviser

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ABSTRACT OF THESIS

Applications for Three-Dimensional Computer
Graphic Cloud Representations
Produced from Satellite Imagery

This research focuses on applications for three-dimensional cloud
representations which are displayed above a topographic surface. The
computer graphic cloud-topography displays are produced using actual
GOES satellite data, Defense Mapping Agency topography data, and
rawinsonde upper air data. Data from these three sources is used to
generate three-dimensional models which mathematically define cloud
cover and topography for a given area. By applying computer graphics
techniques, these three-dimensional models can be displayed as con-
tinuous tone images or perspective line drawings. Satellite data and
topography data, displayed in this manner, produces a realistic depic-
tion of cloud cover displayed above a topographic surface. As for
applications, these displays can be used for cloud studies, briefing
aids, and flight simulations.

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CHAPTER 1

Introduction

In recent years, computer driven image processing systems have been developed which combine computer technology with graphics technology to produce systems capable of displaying a wide variety of digital imagery. As a result, many graphics software packages have been designed to support these systems. Some of the more advanced graphics software packages are capable of displaying three-dimensional (3-D), mathematically defined models as continuous tone images or perspective line drawings. In the work covered by this thesis, computer graphics technology is applied to produce integrated cloud-topography displays from actual GOES satellite data and topography data. In order to do this, clouds and topography have to be mathematically defined in three dimensions.

In this research process, two-dimensional (2-C) satellite images and 2-D topographic images are used to produce 3-D, mathematically defined, cloud-topography models. High resolution (512 x 512), topographic images are produced which represent the earth's terrain over a 4.27 x 4.27 degree area. These topographic images, mapped in a Mercator projection, can be produced for all areas in the continental United States. GOES infrared and visible images, remapped into a

Mercator projection, are produced which represent cloud cover data over the same 4.27 x 4.27 degree area. These Mercator projection images accurately overlay each other. By displaying these images in succession using an image processing system, cloud cover and cloud features can easily be associated with effects from underlying topographic features. More importantly, by having these images accurately overlay each other, cloud cover information can be obtained with respect to topography. Information, contained in the above Mercator projection images, plus rawinsonde upper air data is used to mathematically define 3-D cloud-topography models for sub-areas within the 4.27 x 4.27 degree areas. These 3-D cloud-topography models represent the cloud cover and topography within the given sub-area and can be displayed using MOVIE.BYU software.

MOVIE.BYU is a graphics software package which was developed at Brigham Young University. It is used in this research to manipulate, rotate, illuminate, and display these mathematical models using the VAX 11/780 computer and the COMTAL image processing system. MOVIE displays these 3-D models on the COMTAL as either continuous tone images or perspective line drawings.

Three-dimensional cloud-topography models, displayed by MOVIE, create a realistic depiction of cloud cover above a topographic surface. Because of the display's enhanced information content and visual appeal, this thesis focuses on applications for satellite data displayed in this manner. Applications described in this thesis include: cloud studies, briefing aids, and flight simulations. The following five chapters discuss the data, recources, software, and

methodology used to create the 3-D cloud-topography model. Chapter 7 describes the applications for these models. Included are examples which illustrate how the cloud-topography model can be used. Finally, Chapter 8 contains a summary of work covered by this research. Suggestions for improvement are included along with suggestions for future work in this area.

CHAPTER 2

Data

Three data sources are used to create the 3-D cloud-topography models. These include: Defense Mapping Agency topography data, rawinsonde upper air data, and GOES satellite data. These data sources along with data acquisition procedures are described in the following sections.

A. Topography Data

The Defense Mapping Agency (DMA) read elevation data from 1:250,000 scale topographic maps for every 30 seconds of latitude and longitude in the continental United States, parts of southern Canada, and parts of northern Mexico. Individual elevations within this data set were read in feet, to the nearest increment of 20. These values represent elevations at specific geographical points and are not average values.

The magnetic tape containing this data was obtained from the National Center for Atmospheric Research (NCAR). The tape consists of 1099 tape blocks, each of which, contains all the elevation data for a 1 x 1 degree square. Data is included for a region from $23^{\circ}N$ to $51^{\circ}N$ and from $130^{\circ}W$ to $60^{\circ}W$. The tape blocks are organized starting in the southwest corner of the region, scan eastward to the eastern boundary,

then 1 degree north from the start and eastward again. A total

of 28 of these west-east scans are made. Tape blocks which only con-

tain sea level data are omitted. Figure 2-1 shows regions where

topography data is available.

Each tape block contains a latitude and longtiude followed by

14641 consecutive elevations. The latitude and longitude specify the

geographical location of the 1 x 1 degree squares. The elevations

contained in a tape block are organized starting in the southwest

corner of the 1 x 1 degree square, scan eastward to the eastern boun-

dary of the 1 x 1 degree square, then move 30 seconds north from the

start and eastward again. A total of 121 west-east scans are made.

Boundary values in each 1 x 1 degree square are repeated in adjacent

1 x 1 degree squares (Joseph, 1982).

B. Rawinsonde Data

The National Weather Service (NWS) maintains a network of

rawinsonde stations which send rawinsondes aloft twice daily at 0000

GMT and 1200 GMT. These rawinsondes contain an instrument package and

a radio transmitter. The instrument package contains instruments

which measure temperature, pressure, and humidity throughout the tro-

posphere and lower stratosphere. As the rawinsonde ascends through

the atmosphere, the radio transmits these measurements back to the

station where the measurements are recorded, encoded, and transmitted

to users. Rawinsonde data, collected in this manner, is divided into

two types: mandatory level data and significant level data.

Mandatory level reports contain observations from ten specific

atmospheric pressure levels: 1000, 850, 700, 500, 400, 300, 250, 200,
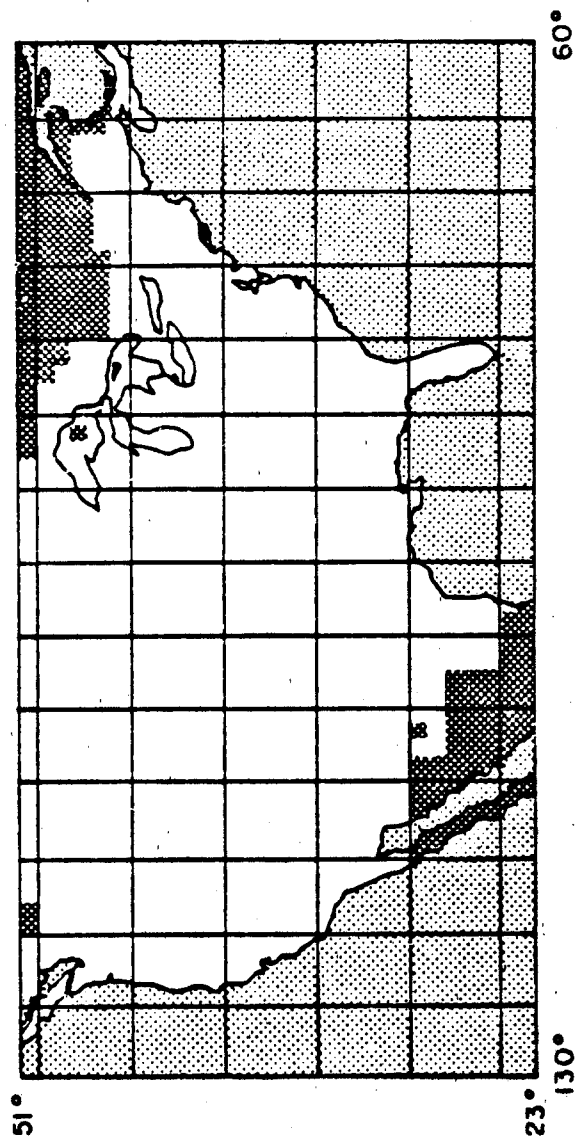
Figure 2-1
Available topographic data
(adapted from Joseph, 1982)

150, and 100 mb. For each level, temperature, wind direction and speed, dew point depression, and height of the pressure surface are reported. In addition, surface information and tropopause information are included in the reports.

Significant level reports contain data for any level where important changes in the temperature, humidity, and wind profiles occur. This report contains two sections, one for reporting temperature and humidity, and the other for reporting wind profiles.

The CSU Atmospheric Science Department receives this data from the FAA604 weather circuit. The data is received via a three-meter antenna, processed by the VAX 11/780 computer, and stored on disk. In this research, only mandatory level data is used.

C. Satellite Data

The National Oceanographic and Atmospheric Administration (NOAA) operates two geostationary meteorological satellites (GOES) which orbit the earth at an altitude of 35000 kilometers above the earth's equator. Since the satellites orbital period is synchronous with the earth's rotation rate, the satellites remain stationary relative to fixed locations on earth. One satellite is positioned near 75°W longitude and given the designation of GOES-East. The other is positioned near 135°W longitude and designated as GOES-West (Epstein et al., 1984). Currently, GOES-East is not operational and GOES-West is positioned near 110°W longitude.

The instrument flown aboard the GOES satellite is the Visible Infrared Spin Scan Radiometer (VISSR). The VISSR consists of a mirror

that is stepped to provide north-south viewing of the earth while satellite rotation provides west-east scanning. The mirror is stepped one notch following a west-east scan. A total of 1821 of these west-east scans make up a full frame image of the earth. Normally, a complete full frame image is scanned every 30 minutes, 24 hours a day, seven days a week.

Radiation received by the mirror is reflected into a 16-inch diameter telescope. A fiber optics bundle is used to couple the telescope to eight visible band detectors sensitive to visible radiation (.54 - .70 μm). Germanium relay lenses are used to pass infrared radiation through optical filters, providing a 10.5 - 12.6 μm band pass, to the infrared detector.

The visible detector has a nominal resolution of about one kilometer while the infrared detector has a resolution of only about eight kilometers. The infrared data is oversampled in the west-east scan. As a result, the sampling resolution is four kilometers in the west-east direction. Therefore, at the sub-satellite point, visible data has a one kilometer ground resolution and infrared data has a 8 x 4 kilometer ground resolution (Hord, 1982). Ground resolution decreases away from the sub-satellite point due to the curvature of the earth.

Output from the infrared and visibile detectors is digitized on the satellite and transmitted to a satellite ground station at Wallops Island, Virginia. There, navigation parameters are added. The data is formatted, calibrated, and retransmitted back to the satellite for relay to other users.

As the data is relayed, the CSU Atmospheric Science Department's Direct Satellite Readout Ground Station (DSRGS) collects, processes,

and stores this data. The DRSGS basically consists of the following components: two dish antennas to receive the data, two PDP 11/34 computers to process the data, and three disks to store the data. A ten-meter dish antenna is positioned to receive data from the GOES-West satellite and a five-meter dish antenna is positioned to receive data from the GOES-East satellite. In normal operational mode, only one DEC PDP 11/34 computer is needed to process this data since GOES-East data is transmitted on the hour and half hour, while the GOES-West data is transmitted at 15 minutes past the hour and 45 minutes past the hour. The other DEC PDP 11/34 is used as a backup to insure data collection continues if one of the components within the system fails or needs maintenance. Data received by DRSGS can be stored on disk, 9-track magnetic tape, or transferred to the IRIS system where the data can be displayed (Laybe, 1983). A block diagram of the DRSGS/IRIS system is shown in Figure 2-2.
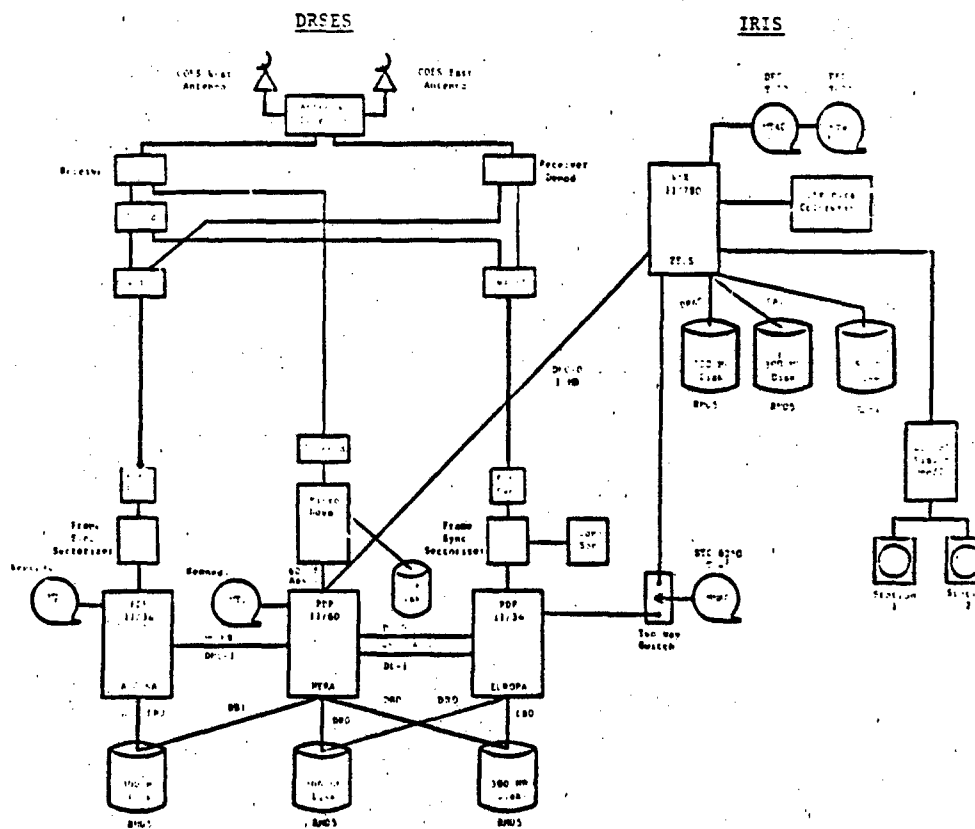
Figure 2-2
Block diagram for DRSGS/IRIS system

CHAPTER 3

Interactive Research Imaging System (IRIS)

The Interactive Research Imaging System provides the data manipu-
lation capability and the image processing capability to create and
display 3-D cloud-topography models. The Interactive Research Imaging
System consists of two main components, the VAX 11/780 computer and
the COMTAL Vision One/20 image processing system. Since these two
resources were used extensively in the research process, they warrant
further explanation. In addition, a description is included on how
these resources are used to display the 3-D cloud-topography models.

A.   VAX 11/780 Computer

At the heart of the Interactive Research Imaging System
(IRIS) is the DEC VAX 11/780 computer. This mid-size computer
features a 32-bit processor which possesses sufficient computing speed
for many meterological and image processing applications. Perhaps the
VAX 11/780's most attractive feature is the VAX/VMS Operating System.
This operating system allows very large programs to run efficiently by
using a virtual memory system. With this system, the VAX 11/780 uses
disk storage to extend main memory onto disk. To the user, it appears
the systems main memory is unlimited in size (Staff, Digital Equipment
Corporation, 1982).

The CSU Atmospheric Science Department's VAX 11/780 is configured with 3 megabytes of main memory along with 1.1 gigabytes of disk storage capacity. Two DEC TU77 tape drives provide additional storage capacity in the form of a 9-track magnetic tape and provide a medium to enter data onto the system. A communication link from the VAX 11/780 to the DRSGS's PDP 11/60 provides a means by which satellite data, collected by DRSGS, can be transferred to IRIS. Another link from the VAX to the COMTAL Vision One/20 image processing system provides a means to display data received from the DRSGS. One additional link from the VAX to the Colowrite C-4300 (Optronics) provides a means to obtain hard copy, high resolution, color transparencies of imagery displayed on the COMTAL monitor. A block diagram of the DRSGS/IRIS system is shown in Figure 2-2.

The CSU VAX 11/780 supports two high level languages, VAX FORTRAN and VAX PASCAL, and one assembly level language, VAX-11 Macro. All software used to create and display the 3-D cloud-topography model is supported by VAX FORTRAN.

B.   COMTAL Vision One/20

Another key component of the IRIS system is the COMTAL Vision One/20 image processing system. This system produces high resolution (512 x 512) imagery over a full range of brightness values in shades of grey or pseudocolor. Although the COMTAL Vision one/20 is a standalone system which performs a multitude of image processing operations by itself, it can be interfaced with the VAX 11/780 as host. This feature gives the COMTAL/VAX configuration exceptional image processing and display capability.

Digital imagery (i.e. imagery which is obtained by partitioning the area of one image into a finite two-dimensional array of small, uniformly shaped, mutually exclusive regions called pixels) can be created and displayed on the COMTAL monitor using an image plane (512 x 512 x 8 bits). By assigning 8 bits to each pixel in an image plane, 256 (2^8) grey shades are possible. These images can be displayed on the COMTAL monitor as monochrome images or as pseudocolor images.

Monochrome images, defined by eight pixels, can show 256 levels of greyness. Each pixel making up the image can be black (pixel value = 0), white (pixel value = 255), or any level of greyness in between.

Pseudocolor images are obtained by arbitrarily adding color to the monochrome images. These pseudocolor images are produced by the COMTAL's pseudocolor processor. This processor accesses a red, green, and blue pseudocolor memory which, when activated, produces signals to the red, green, and blue guns in the color monitor. Each of the pseudocolor memories contain 256 8 bit locations which correspond to a level of greyness in the monochrome image. Each location in a pseudo- color memory contains a value from 0-255 specifying the intensity of the color produced by the gun. When the memories are activated by the pseudocolor processor, the values of pixels making up the monochrome image are indexed into the red, green, and blue pseudocolor memories. Then, the red, green, and blue guns are each fired at the specified intensity creating a pseudocolor image by exciting a combination of red, green, and blue phosphors on the screen.

A digital image can also be represented by a graphics plane (512 x 512 x 1 bits). Since each pixel is specified by only one bit, two

(2^1) grey shades are possible. A pixel represented in this way appears either black (pixel value = 1) or white (pixel value = 0). Digital images which are defined in this manner are termed "COMTAL graphics" or "graphics". These graphics often contain line drawings, grid lines, or labels. Since the COMTAL stores a color attribute for the graphic as a whole, an entire graphic can be set to any of 16 colors. Another COMTAL feature allows the user to overlay a graphic on a monochrome or pseudocolor image. This capability gives the user the ability to label and grid monochrome and pseudocolor images without destroying any of the images original information content (Staff, COMTAL Corporation, 1982).

C. Display Methods

The VAX/COMTAL systems are used to display the 2-D Mercator projection imagery and the 3-D cloud-topography models. This section describes how the two systems are used to produce these displays.

Mercator projection images are created on the VAX 11/780 computer and displayed on the COMTAL as a monochrome images. In this thesis, these images often appear with one or more COMTAL graphics overlaid onto the monochrome image. These graphics contain either labels, state boundaries, or other representations.

Cloud-topography models are created on the VAX 11/780 computer and displayed on the COMTAL as pseudocolor images, COMTAL graphics, or a combination of both. A 3-D model displayed as a pseudocolor image contains a continuous tone representation of the model. A 3-D model displayed as a COMTAL graphic contains a contour line respresentation

of the model. Most of the cloud-topography displays appearing in this thesis were displayed on the COMTAL monitor as a pseudocolor image overlaid by one or more COMTAL graphics. When displayed as a pseudo-color image, topographic bases are colored green and cloud representations are colored white. To increase the display's perspective, contour lines, which are written to a COMTAL graphic, are overlaid onto the pseudocolor image. The COMTAL graphic overlaying the clouds is colored white, while the COMTAL graphic overlaying the base is colored green. This display method increases the display's perspective and visual appeal, plus adds a grid to the topographic base for quantitative scaling.

CHAPTER 4

Software

An extensive amount of software was used in the process of
creating and displaying the 3-D cloud-topography models. Software
falls into three main groups: IRIS Software, MOVIE.BYU Graphics
Software, and User Software which was written by the author. The
major programs within each group are discussed with respect to purpose
and function.

A.   IRIS Software

IRIS applications programs are designed to process, manipu-
late, and display satellite data received by the Direct Readout
Satellite Ground Station (DRSGS). These programs are executed using
the Transportable Applications Executive (AE). TAE is a set of exe-
cutive programs which interact with the user to manage the execution
of applications programs. The main advantage of TAE is that it provi-
des a menu driven, user friendly means to run applications programs.
TAE is also interfaced with an IRIS data base. This data base is used
by the applications programs to store satellite image navigation
parameters, image file attributes, and other information describing
satellite data sets. In this research, IRIS applications programs are

used: 1) to create digital images from raw satellite data, 2) to display the digital images on the COMTAL, 3) to create IRIS data base entrys defining image attributes, and 5) to plot geopolitical boundaries on COMTAL graphics. Applications programs performing these functions are described below.

CSUGOES

Raw GOES satellite data, which has been received by the DRSGS, is read from either disk or magnetic tape and processed by the CSUGOES program. This program produces image files which can be displayed on the COMTAL monitor. With each image file, automatic navigation parameters are also read into the IRIS data base.

WINDOW

Data processed by CSUGOES can be displayed on the COMTAL by the WINDOW program. WINDOW creates a sub-image by extracting a subset of data from an exisiting image. The program modifies the apparent resolution of the data to make the sub-image fit exactly into a 512 x 512 image plane. If the original image was smaller than 512 x 512 pixels, WINDOW can be used to expand the image to fit into the 512 x 512 image plane. If the original image is larger than 512 x 512 pixels, WINDOW shrinks the image to fit into the 512 x 512 image plane. The resulting sub-image is displayed on the COMTAL monitor.

REMAP

Satellite data which has been processed through CSUGOES can be remapped into various projections using the REMAP program. In this research, REMAP is used to remap satellite data into Mercator projection images covering a 4.27 x 4.27 degree area. These remapped Mercator projection images can be displayed on the COMTAL monitor by using WINDOW.

DEFSCT

DEFSCT is used to define output image file attributes for the REMAP program. Parameters entered into the DEFSCT program define the location of the 4.27 x 4.27 degree area for the output image file. Other parameters define the projection of the output file. These parameters are stored in the IRIS data base.

GPPLOT

Images which are displayed on the COMTAL can be gridded by plotting geopolitical boundaries on them using the GPPLOT program. These boundaries are usually written to a COMTAL graphic.

B.   MOVIE.BYU Software

MOVIE.BYU is a general purpose graphics package used to create, manipulate, and display 3-D mathematical models. The software package consists of a total of seven programs, of which, only DISPLAY was used in this research. DISPLAY is the largest and most sophisticated program in the package and, as the name implies, is used to display the 3-D cloud-topography models.

DISPLAY

The particular version of DISPLAY used in this research was obtained from the CSU Electrical Engineering Department. This version was originally configured to interface with the RAMTEK 9050 graphics device. Since no RAMTEK devices were available at the CSU Atmospheric Science Department and no COMTAL interfaces were commercially available, DISPLAY was modified to interface with the COMTAL.

Three-dimensional, mathematically defined models can be manipulated and displayed using the DISPLAY program. Models are made up of a series of three and four sided polygonal elements which are used to define model surfaces. Each element consists of three or four nodes which represent intersection points where the sides of the elements meet. To define a model, the X, Y, and Z coordinates of each node in the model must be defined and stored in a coordinate array. To complete the model description, the exact sequence in which nodes are to be connected to form polygons must be specified and stored in a connectivity array. A model can further be broken down into parts. Parts may be defined by grouping contiguous polygonal elements. These groups are specfied and stored in a parts array. The coordinate array, the connectivity array, and the parts array completely describe the model mathematically and are stored in a geometry file.

Models described in the above manner can be viewed on the COMTAL monitor using DISPLAY. When displayed, models appear as either continuous tone images or perspective line drawings. A total of 39 interactive commands are available to the user to specify how the model is to be displayed. The SCOPE command is used to specify the

output device and to specify whether the model is to be displayed as a
continuous tone image or perspective line drawing. The PARTS command
allows the user to withhold model parts from the display. Other com-
mands are available to manipulate the model. The ROTATION,
TRANSLATION, FIELD, and DISTANCE commands allow the user to view the
model from virtually any position. Still other commands allow the
selection of color and shading for continuous tone imagery. The COLOR
command is used to specify colors by part along with background color.
Colors are specified as mixtures of the three primary colors, red,
green, and blue. Model illumination can be specified by the LIGHT
command. Up to four light sources can be arbitrarily defined in
space. The VIEW command is used to display the model on the COMTAL
color monitor (Christianson and Stephenson, 1981).

C. User Software

A total of eight user programs are used in this research.
Seven of them are used to create the 3-D cloud-topography models.
The other program is used to illustrate an application for the
cloud-topography model. User software is compatable with both the
MOVIE.BYU Graphics Software and the COMTAL image processing system.
These eight programs are described briefly below.

DMA512

DMA512 is a user interactive program used to create 2-D, Mercator topographic images. These images represent the earth's terrain and cover a 4.27 x 4.27 degree area. The exact location of the area covered by the topographic image is specified by entering a reference latitude and longitude which defines the northwest corner of the 4.27 x 4.27 degree area. After the reference latitude and longitude is specified, DMA512 extracts the appropriate elevation data from the DMA data tape, scales the data, and formats the data as a 512 x 512 COMTAL image. This COMTAL image is written to an output file. Scaling parameters are also written to this file. Information contained in this image file is later used by another program to mathematically define 3-D topography models.

SHIFTR

After the REMAP program is used to create a Mercator satellite image, the resulting image may not exactly overlay the Mercator topographic image. If a better fit is desired, SHIFTR can be used to shift or translate a satellite image left or right, up or down, a specified number of pixels. The left-right shift is specified by a number, X. A positive value for X shifts the image to the right X pixels while a negative value shifts the image left. Similarly, the up-down shift is specified by a number, Y. A positive value for Y shifts the image up Y pixels while a negative value shifts the image left. The resulting image is shifted the specified number of pixels.

DEFINE

DEFINE is a user interactive program which is used in the process of generating a 3-D cloud-topography model. DEFINE is used: 1) to display Mercator images on the COMTAL monitor, 2) to specify input and output file names used in the process, and 3) to specify parameters which define a sub-area of a Mercator image to be transformed into three dimensions. DEFINE writes these file names and parameters to an output file. By having this data in a file, it can be accessed by other programs which are used in the process. This alleviates the need to enter file names and parameters more than once.

INTCLD

INTCLD is a user interactive program designed to produce cloud layer files. These files contain cloud top height information and cloud base information which defines cloud cover for the specified sub-area of a Mercator satellite image. INTCLD is used: 1) to determine cloudy and clear pixels within a sub-area of a Mercator satellite image, 2) to determine cloud top heights for cloudy pixels, and 3) to determine cloud base heights for cloudy pixels. INTCLD produces three cloud layer files, each of which, represents cloud cover for a layer in the atmosphere. Information contained in these files is later used by another program to mathematically define 3-D cloud models.

TOPGEN

TOPGEN is a user interactive program designed to produce 3-D topography models. These models mathematically define the

topography for a sub-area of a Mercator topographic image. TOPGEN
extracts the appropriate elevation data from the topographic image,
scales the elevation data, and produces a geometry file which contains
a topography model. This geometry file is written in a MOVIE.BYU
readable format and can be displayed on the COMTAL using the DISPLAY
program.

CLDGEN

CLDGEN is a program designed to produce 3-D cloud models.
These models mathematically define cloud cover for a sub-area of a
Mercator satellite image. CLDGEN reads the three cloud layer files
produced by INTCLD. For each cloud contained in these files, the
program produces a geometry file which contains a 3-D cloud model.
Up to 26 geometry files can be produced. These files are written in a
MOVIE.BYU readable format and can be displayed on the COMTAL using the
DISPLAY program.

MERGER

MERGER is designed to produce a 3-D cloud-topography model.
This model mathematically defines cloud cover and topography for a
sub-area of the Mercator images. MERGER produces this model by com-
bining the 3-D topography model (TOPGEN) and the 3-D cloud models
(CLDGEN). MERGER writes the mathematical description of the 3-D
cloud-topography model to a geometry file. This file is written in a
MOVIE.BYU readable format and can be displayed on the COMTAL using the
DISPLAY program.

FLTRAK

FLTRAK is used to plot a flight track on the 3-D cloud-topography model. These flight tracks mathematically define, in 3-D, an aircraft's path from take-off to landing. This program is discussed further in Chapter 7.

CHAPTER 5

2-D Image Generation

The process of creating a 3-D cloud-topography model begins by
generating a set of three Mercator projection images. These three
images contain topography data from the DMA data set, infrared data
from GOES infrared satellite imagery, and visible data from the GOES
visible satellite imagery. Data contained in these images is used to
define terrain and cloud cover for a 4.27 x 4.27 degree area of the
earth. It is the main concern here that the three images accurately
overlay each other since it is from these images that the 3-D models
will be generated.

At this point, it must be emphasized that the visible satellite
image is not absolutely necessary to generate 3-D cloud-topography
models. The main function of the visible image is to aid cloud
interpretation and image navigation. Therefore, the process of
generating a 3-D model will work equally well using only the
topographic image and the infrared image. However, without the
visible image, the accuracy of cloud interpretation and image naviga-
tion may suffer. The remaining part of this chapter explains how the
Mercator images are generated and navigated.

A. Mercator Topographic Images

The generation process begins by the selection of a 4.27 x 4.27 degree area to be transformed into a 2-D Mercator topographic image. Once the area of interest is selected, the DMA512 program is used to create the topographic image. To specify the area of interest, the latitude and longitude of the northwest corner of this area is entered into the DMA512 program. Once the area is defined, a 512 x 512 array of elevations is extracted from the DMA data tape. These elevations are converted to meters and a scale factor is calculated by dividing the highest elevation in the array by 255. The scale factor is used to scale each elevation in the array from 0 to 255. Once scaling is complete, the data is formatted as a COMTAL image and is written to an output file. The scaling factor and the reference latitude and longitude -- also saved in the file for later use.

A Mercator topographic image is shown in Figure 5-1. This image .epresents the terrain for an area covering southeast Wyoming, southwest Nebraska and northern Colorado. A COMTAL graphic containing state boundaries has been overlaid onto the image. To show the resolution of the image, several geographical features have been labeled.

Each elevation in the image is scaled 0 to 255 and is represented by a pixel grey shade. Data is scaled such that elevation is proportional to grey shade. Lighter grey shades represent higher elevations and darker grey shades represent lower elevations. Each grey shade increment in Figure 5-1 represents a 17.68 meter change in elevation. Individual elevations in the image can be calculated by multiplying the pixel grey shade value by the scale factor (17.68 meters).

Figure 5-1
Mercator topographic image
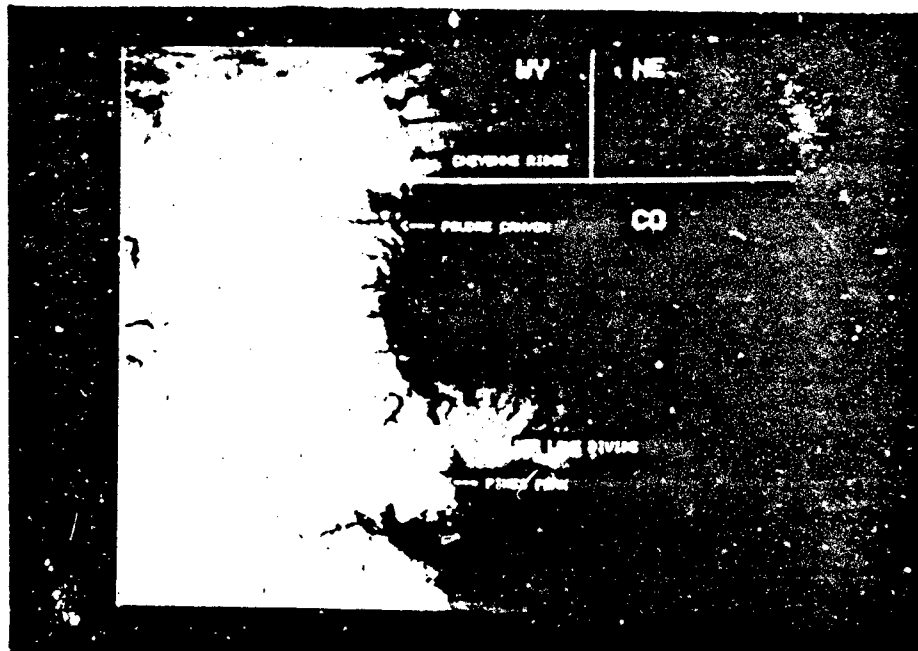
Each pixel in the image represents an elevation which is
separated by 30 seconds of latitude in the north-south direction and
30 seconds of longitude in the east-west direction. Since the lati-
tude and longitude of the pixel in the northwest corner of the image
is known, the latitude and longitude of each pixel in the image can be
calculated by referencing the pixel's X and Y screen coordinates. The
pixel in the northwest corner of the image is referenced by screen
coordinates X = 0 and Y = 0. X screen coordinates increase to the
east (right) and Y screen coordinates increase to the south (down).
Since each pixel is separated by 30 seconds of latitude in the north-
south direction, the latitude of a pixel can be calculated by
multiplying its Y screen coordinate by 30 seconds of latitude and
subtracting the resulting number from the reference latitude.
Likewise, the longitude of a pixel can be calculated by multiplying
its X screen coordinate by 30 seconds of longitude and subtracting the
resulting number from the reference longitude.

Since the elevation and geographical location can be calculated
for each pixel in the image, the image contains all the information
needed to define a topographic surface in three dimensions. Data con-
tained in this image will later be used to define a topographic base
for the 3-D cloud-topography model.

B. Mercator Satellite Images

Now that the topographic image has been generated for a 4.27
x 4.27 degree area, GOES satellite imagery can be collected for this
region. Figures 5-2 and 5-3 show infrared and visible satellite

Figure 5-2
Infrared GOES satellite image for 2132 GMT,
31 October 1984

Figure 5-3
Visible GOES satellite image for 2132 GMT,
31 Ocotber 1984

31 OCT 84
2132 GMT

31 OCT 84
2132 GMT
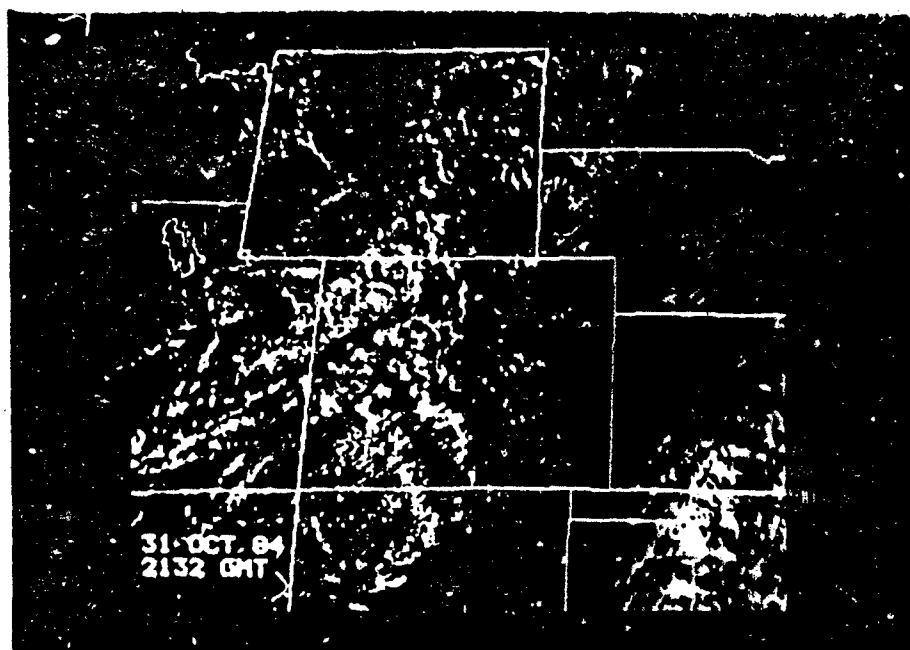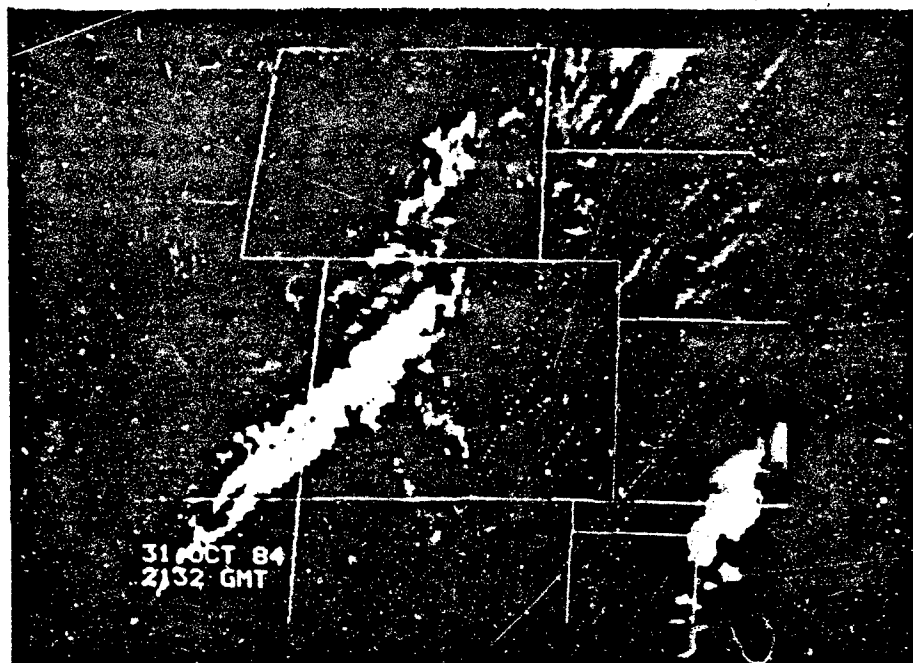
imagery for 2132 GMT, 31 October 84. This data was collected by the DRSGS, processed using CSUGOES, and displayed using WINDOW. This imagery covers a portion of the western United Sates including the area covered by the topographic image shown in Figure 5-1.

The next step in the process is to remap the data contained in these images (Figures 5-2 and 5-3) into a Mercator projection that will accurately overlay the topographic image (Figure 5-1). This is accomplished using the REMAP program. Figures 5-4 and 5-5 show the resulting infrared and visible images after the remapping process. These images were displayed using WINDOW and gridded with state boundaries using the GPPLOT program. By comparing the topographic image (Figuare 5-1) with the visible image (Figure 5-5), it can be seen that the images closely overlay each other.

To show how closely they actually do match, elevations greater than 3589 meters have been blacked out in Figure 5-6. The black area has been made into a COMTAL graphic which can be used as a template to overlay onto the visible image. When this template is overlaid onto the image, the orographically induced clouds covering the mountain ranges should coincide closely with the template. Figure 5-7 shows the visible image after the template is overlaid. From Figure 5-7, it can be seen that the images overlay each other to within several pixels after the remapping process.

Many times, the remapping process is not as accurate as the above example shows. Figure 5-8 is a visible image which has been remapped into a Mercator projection. In this case, mountain ranges are plainly visible. By overlaying the template onto this image, it is apparent

Figure 5-4
Mercator infrared image for 2132 GMT
31 October 1984

Figure 5-5
Mercator visible image for 2132 GMT
31 October 1984

31 OCT 84
2132 GMT
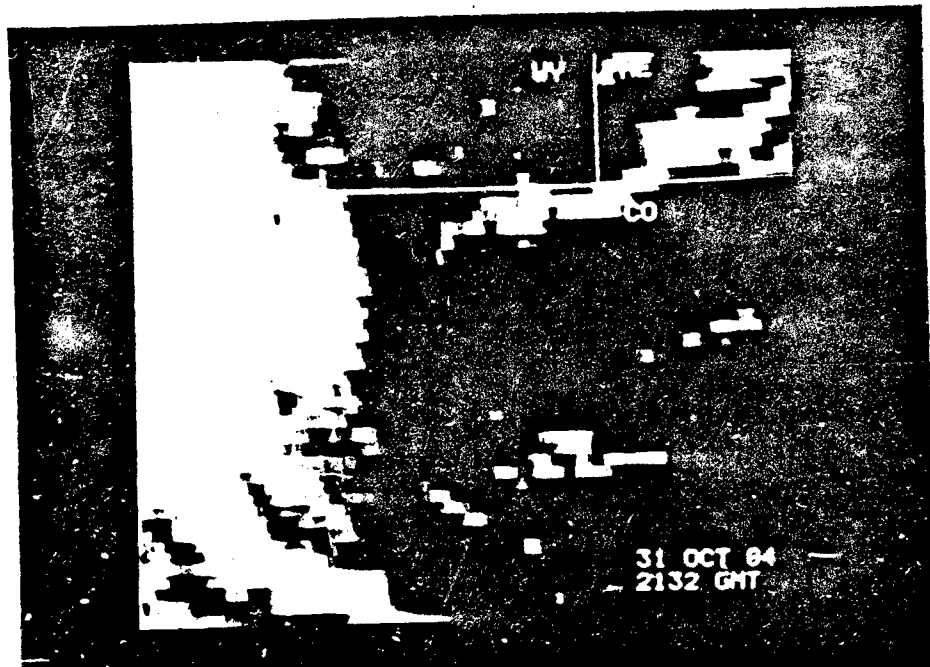
Figure 5-6
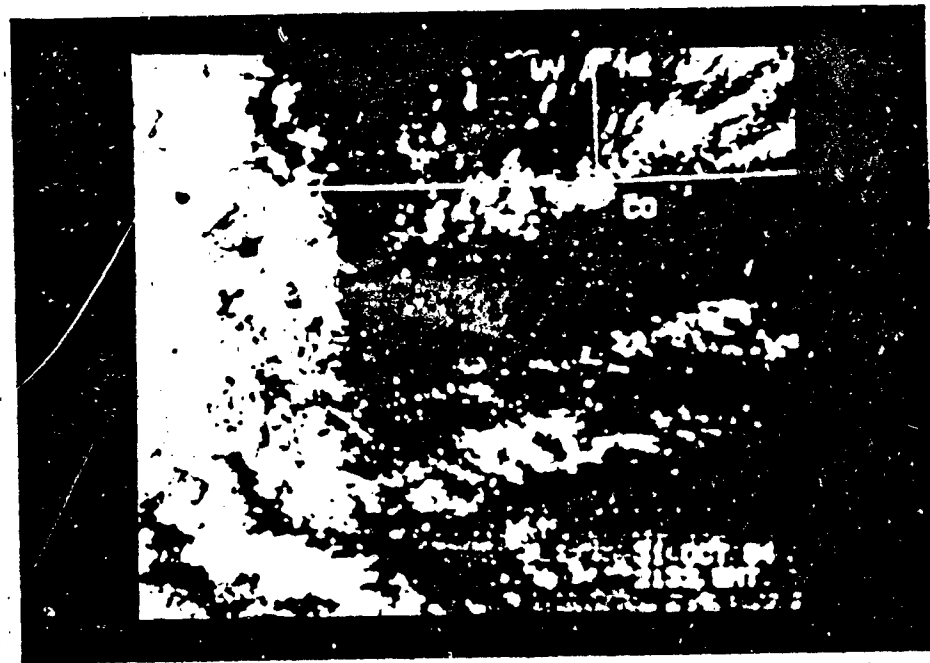Mercator topographic image with template overlaid
representing elevations above 3571 meters.

Figure 5-7
Mercator visible image with 3571 meter template
overlaid.
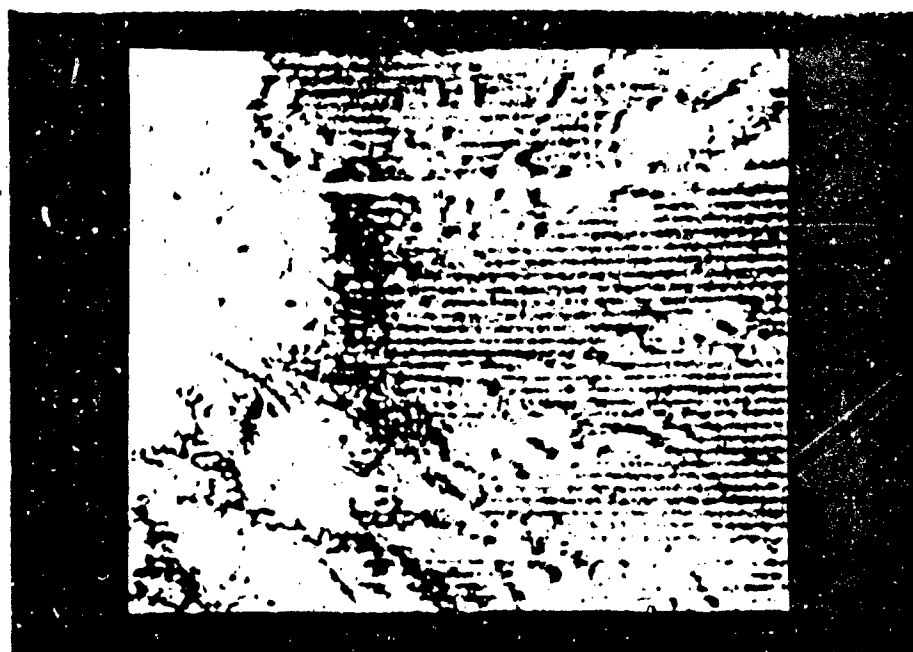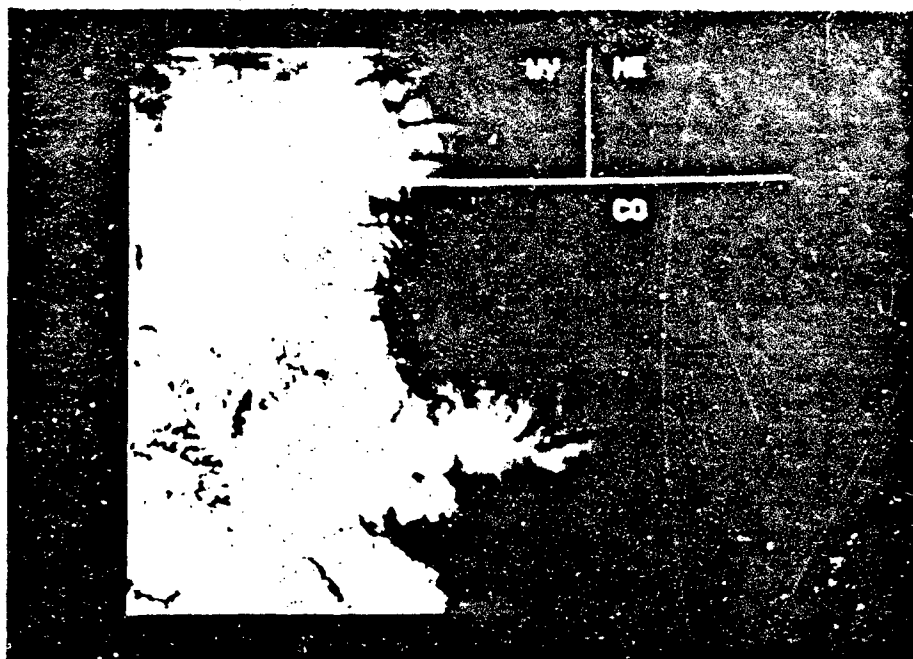
Figure 5-8
Mercator visible image for 1930 GMT, 23 January 85
with 3571 meter template overlaid.

Figure 5-9
Mercator visible image for 1930 GMT, 23 January 85
showing 3571 meter template overlaid after correcting
navigation error.
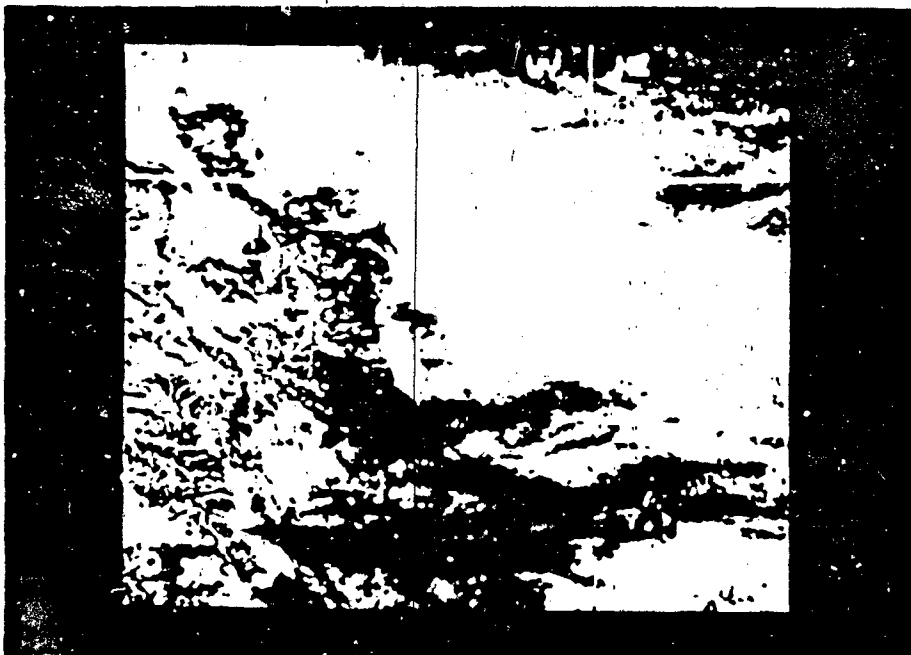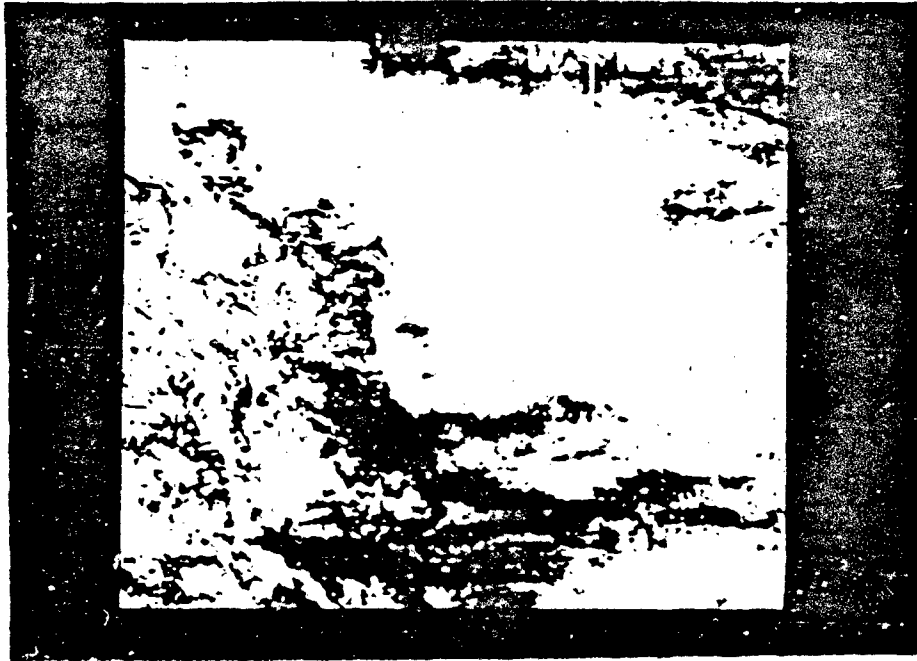
that the image does not overlay the topographic image. To correct the
descrepancy, the SHIFTR program can be used to insure a more accurate
fit. Figure 5-9 shows the same visible image with the black template
after the visible image has been shifted two pixels to the left and
nineteen pixels down. This image accurately overlays the topographic
image.

Since the satellite images accurately overlay the topographic
image, cloud cover data can be obtained with respect to topography.
Data contained in the Mercator infrared image will later be used to
define the cloud representations that will be displayed above the
topographic base.

CHAPTER 6

3-D Model Generation

The previous chapter explained how a set of Mercator projection images is produced. This chapter explains how these images are used to produce 3-D cloud-topography models.

A. Sub-Area Selection

The generation process begins with the selection of a sub-area that is to be transformed into three dimensions. This sub-area can be defined using any of the three Mercator projection images. If the user is interested in a cloud formation, the sub-area may be defined on a satellite image. If the user is interested in the cloud cover over a particular area, the sub-area may be defined on the topographic image. The process for selecting a sub-area is the same.

A sub-area can be selected for essentially any area covered by a Mercator projection image. The sub-area can include any 16 x 16, 32 x 32, 64 x 64, 128 x 128, 256 x 256, or 512 x 512 pixel area within the Mercator image; however, the sub-area must remain within the bounds of the image. The location of this area can be defined using the program, DEFINE, which first displays the desired images on the COMTAL. The location of the sub-area is defined by specifying an X

and Y screen coordinate for the northwest corner of the sub-area and a side length. The X and Y screen coordinates can be determined using the cursor control device. By placing the cursor over the northwest corner of the desired sub-area, the cursor control device will return the X and Y screen coordinates of the cursor position. The side length for the sub-area is specified by the number of pixels along one side of the sub-area. Choices are 16, 32, 64, 128, 256, and 512. Once the X and Y screen coordinates and the side length are entered into DEFINE, a box is drawn around the selected sub-area. If the displayed sub-area is not acceptable, another one can be defined. Figure 6-1 shows a sub-area displayed on the Mercator infrared image (Figure 5-4). In this case, the sub-area encompasses the entire image. Parameters defining the sub-area are: X screen coordinate = 0, Y screen coordinate = 0, and side length = 512.

Since MOVIE.BYU software is only configured to display sub-areas up to and including 64 x 64 pixels, any sub-areas which are larger than 64 x 64 pixels must be reduced to a smaller array size. This is done by specifying a reduction factor which defines the amount by which the original array is to be reduced. For example, in Figure 6-1, the defined sub-area is 512 x 512 pixels. A reduction factor of 16 averages each 16 x 16 square in the sub-area to a single smoothed pixel. The result is that the entire 512 x 512 pixel sub-area is reduced to a 32 x 32 array of pixels. If the defined sub-area is 32 x 32 pixels or 64 x 64 pixels, a reduction factor can optionally be selected. The final result of data reduction is that the data

Figure 6-1
Mercator infrared image for 2132 GMT, 31 October 84
with white box showing defined sub-area.
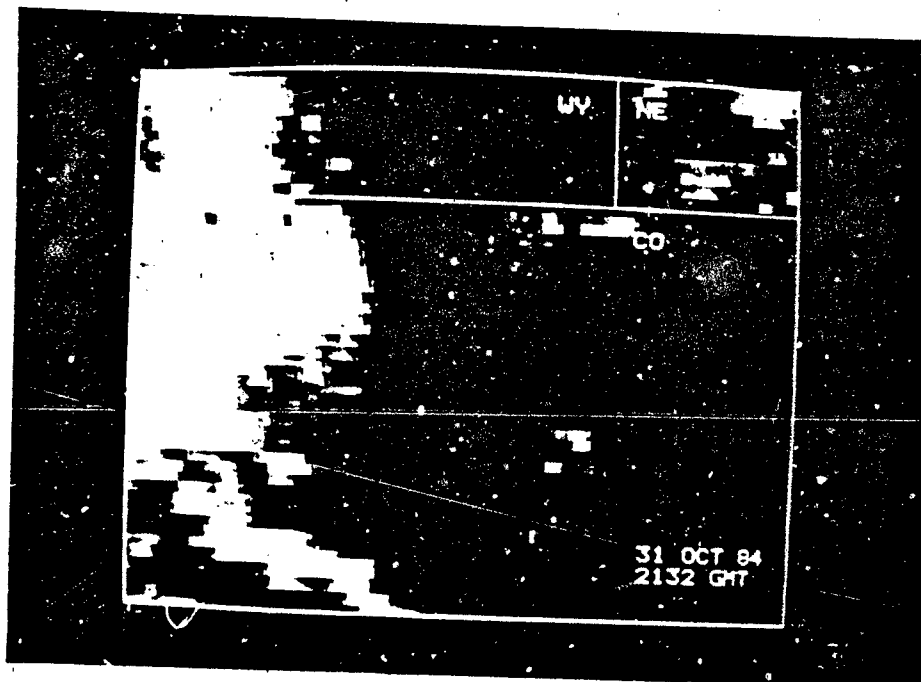
contained in every sub-area is reduced to a 16 x 16, 32 x 32, or
64 x 64 array of pixels.

The reduction factor is specified at the time the sub-area is
defined using the DEFINE program. The DEFINE program allows the user
to only enter a reduction factor that results in a 16 x 16, 32 x 32,
or 64 x 64 array of pixels. After the reduction factor is entered,
DEFINE stores the X and Y screen coordinates, the side length, and
reduction factor in a file where the data can be accessed by other
programs used to create the 3-D cloud-topography model.

B.   Cloud/No Cloud Threshold Selection

After the sub-area is defined, cloud cover for this area is
defined by determining which pixels are cloudy. Cloud/no cloud deter-
minations are based on a simple threshold technique. This technique
involves using either a threshold radiance count from the infrared
image or a threshold brightness count from the visible image to make
the cloud/no cloud determination. Pixels with radiance counts
(brightness counts) greater than or equal to the threshold are con-
sidered cloudy. Pixels with radiance counts (brightness counts) less
than the threshold are considered cloud free.

The cloud/no cloud threshold is specified by using the INTCLD
program. INTCLD begins by letting the user display the desired images
on the COMTAL. Once the images are displayed, the user inspects the
imagery and interprets what is cloud and what is not. The cursor
control device can be used as an aid to determine the cloud/no cloud
threshold. By placing the cursor over the threshold radiance grey

shade (brightness grey shade) the cursor control device will return the value of the radiance count (brightness count) at the cursor position. This value is entered into the INTCLD program.

After the cloud/no cloud threshold is entered, INTCLD extracts the visible and infrared data from the sub-area defined on the Mercator satellite images. If a reduction factor greater than one was specified, the data within the defined sub-area must be reduced in size. Recall that the reduction factor specifies the amount of by which the original sub-area is to be reduced. Thus, if a reduction factor of 16 is specified, every 16 x 16 square in the sub-area is averaged to a single smoothed pixel. For satellite data, data reduction is done by averaging the individual pixels within a square using the following scheme: If fifty percent or more of the individual pixels in a square are equal to or greater than the cloud/no cloud threshold, the resulting smoothed pixel is considered cloudy. The radiance count (brightness count) for this cloudy pixel is calculated by averaging the radiance counts (brightness counts) of those individual pixels equal to or greater than the cloud/no cloud threshold. If less than fifty percent of the individual pixels within a square is equal to or greater than the cloud/no cloud threshold, the resulting smoothed pixel is considered clear. The radiance count (brightness count) for this clear pixel is calculated by averaging all of the pixels within a square.

After all the data in the sub-area is reduced in the above manner, the result is a 16 x 16, 32 x 32, or 64 x 64 array of smoothed pixels. This array can be displayed on the COMTAL as a reduced image. Figure 6-2 shows the reduced infrared image for the sub-area shown in

Figure 6-2
Reduced infrared image for 2132 GMT, 31 October 84.

Figure 6-3
Reduced infrared image for 2132 GMT, 31 October 84
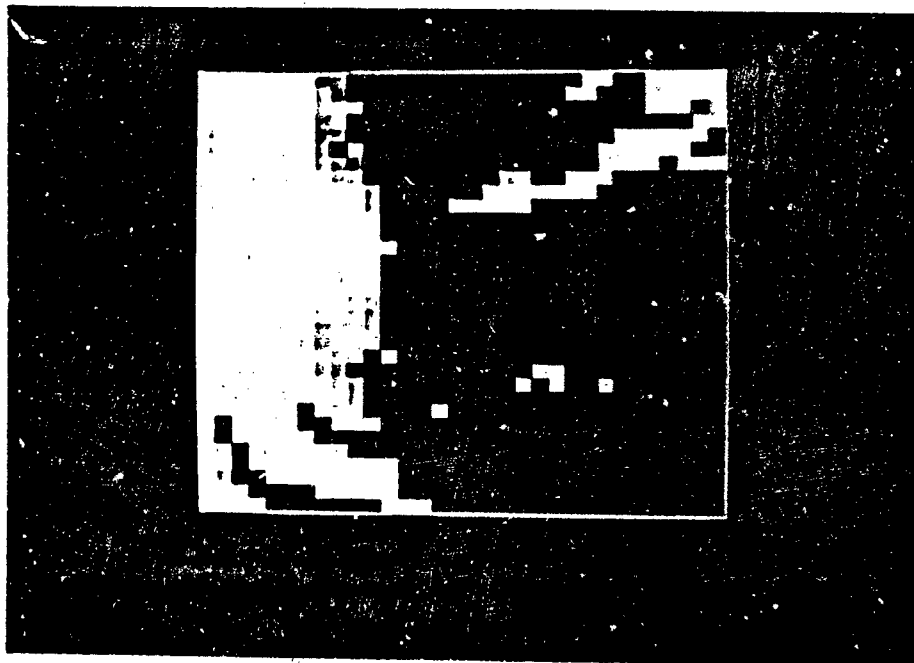with cloud/no cloud threshold applied.

Figure 6-1. Individual pixels within the reduced 32 x 32 array have been duplicated by a factor of 8 (i.e. each pixel in the 32 x 32 array is duplicated to an 8 x 8 pixel array, thus producing a 256 x 256 pixel image). This is done only to enlarge the viewing area.

The final step in the cloud/no cloud determination process is to apply the cloud/no cloud threshold to the reduced infrared image. Figure 6-3 shows the same reduced infrared image in Figure 6-2 after the cloud/no cloud threshold is applied. In Figure 6-3, all smoothed pixels in the reduced infrared image that are below the cloud/no cloud threshold have been set equal to 0 and appear black. Radiance counts associated with each cloudy pixel in the reduced infrared image are later related to temperature and are used to determine cloud top heights.

C.   Cloud Top and Base Height Calculations

The next step in the process of creating a 3-D cloud-topography model is to determine cloud top heights and cloud base heights for each of the cloudy pixels within the reduced infrared image (Figure 6-3). This is done by relating pixel radiance counts to temperature. The resulting temperatures are then related to height using rawinsonde sounding data.

The radiance counts associated with a GOES infrared image correspond to a defined set of equaivalent black body temperatures. This information is summarized in a calibration table which contains a range of radiance counts and their corresponding black body

temperatures. Table 6-1 shows the standard infrared calibration table used in this research. The accuracy of these temperatures is limited to two to four degrees Kelvin (K), generally, nearer two degrees K in winter and four degrees K in summer (Hord, 1982). The INTCLD program uses data contained in Table 6-1 to calculate cloud top temperatures for each cloudy pixel in the reduced infrared image.

After all the cloud top temperatures are determined, the next step is to relate these temperatures to heights using an atmospheric profile of temperature versus height. Atmospheric profiles of temperature versus height are obtained from rawinsonde upper air data. Here, a sounding is selected that is both near in proximity to the area of interest and close to the valid time for the satellite image. Once the sounding is selected, it is retrieved from a disk file on the VAX and the mandatory level data is manually decoded. Decoded data is entered into a file which is read by the INTCLD program. INTCLD processes this sounding data to eliminate surface inversions and other inversions that may occur in the troposphere. Missing levels are also eliminated in the process. The resulting sounding has a negative lapse rate throughout the depth of the troposphere. This insures that only one cloud top height can be assigned for a given cloud top temperature.

Figure 6-4 shows a temperature versus height profile. This profile was selected for determining cloud top heights for the sub-area shown in Figure 6-1. This profile was created from a Denver, Colorado rawinsonde sounding valid for 1200 GMT, 31 October 84. Figure 6-5 shows the same Denver sounding after having been processed by INTCLD. Notice that the surface inversion has been eliminated.

Table 6-1

Standard infrared calibration table (from Clark, D. J., 1983)

STANDARD IR CALIBRATION

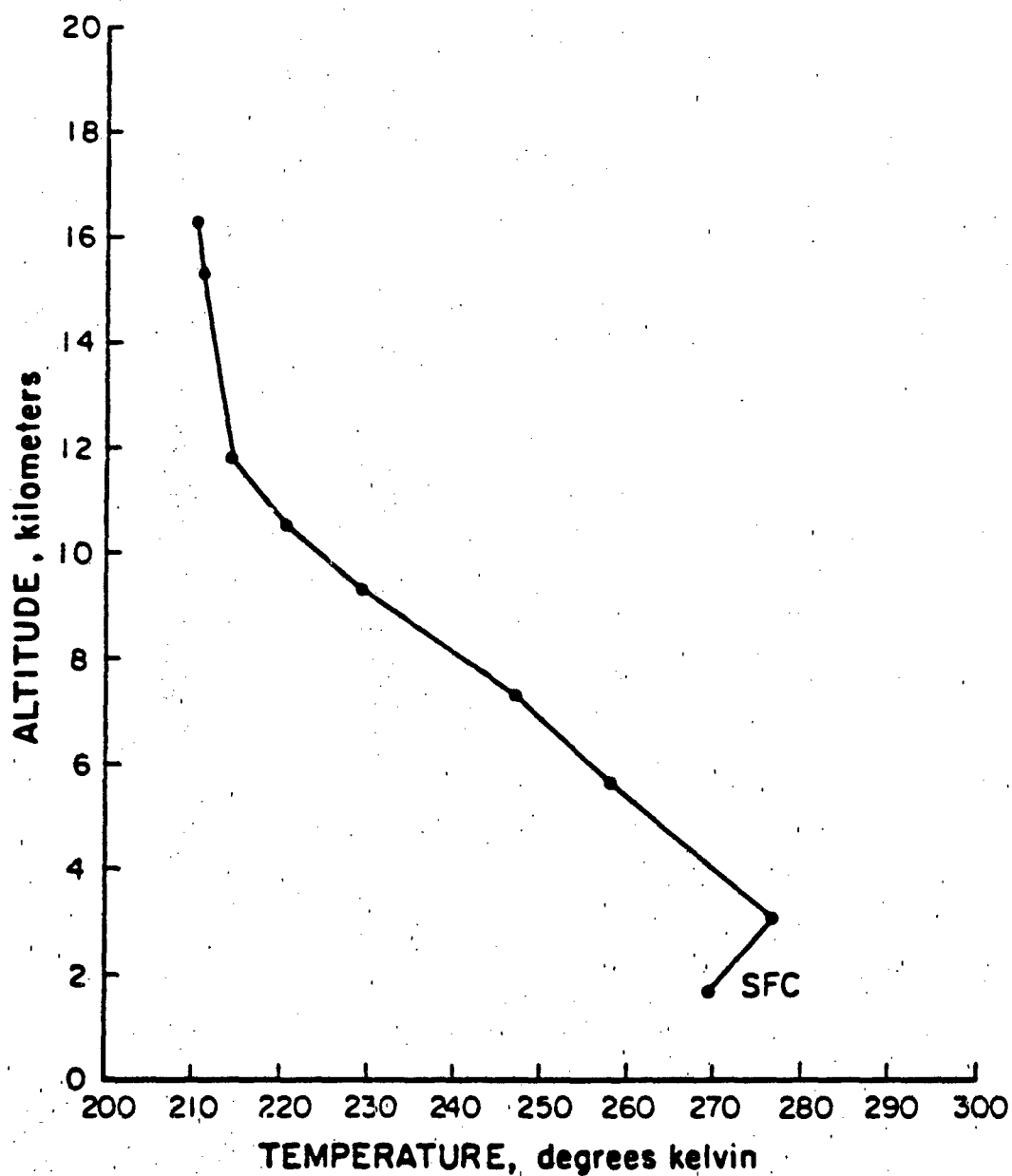| FAHRENHEIT	CENTIGRADE	KELVIN	COUNT VALUE
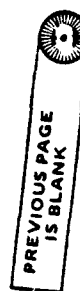
Figure 6-4
Temperature versus height profile for Denver,
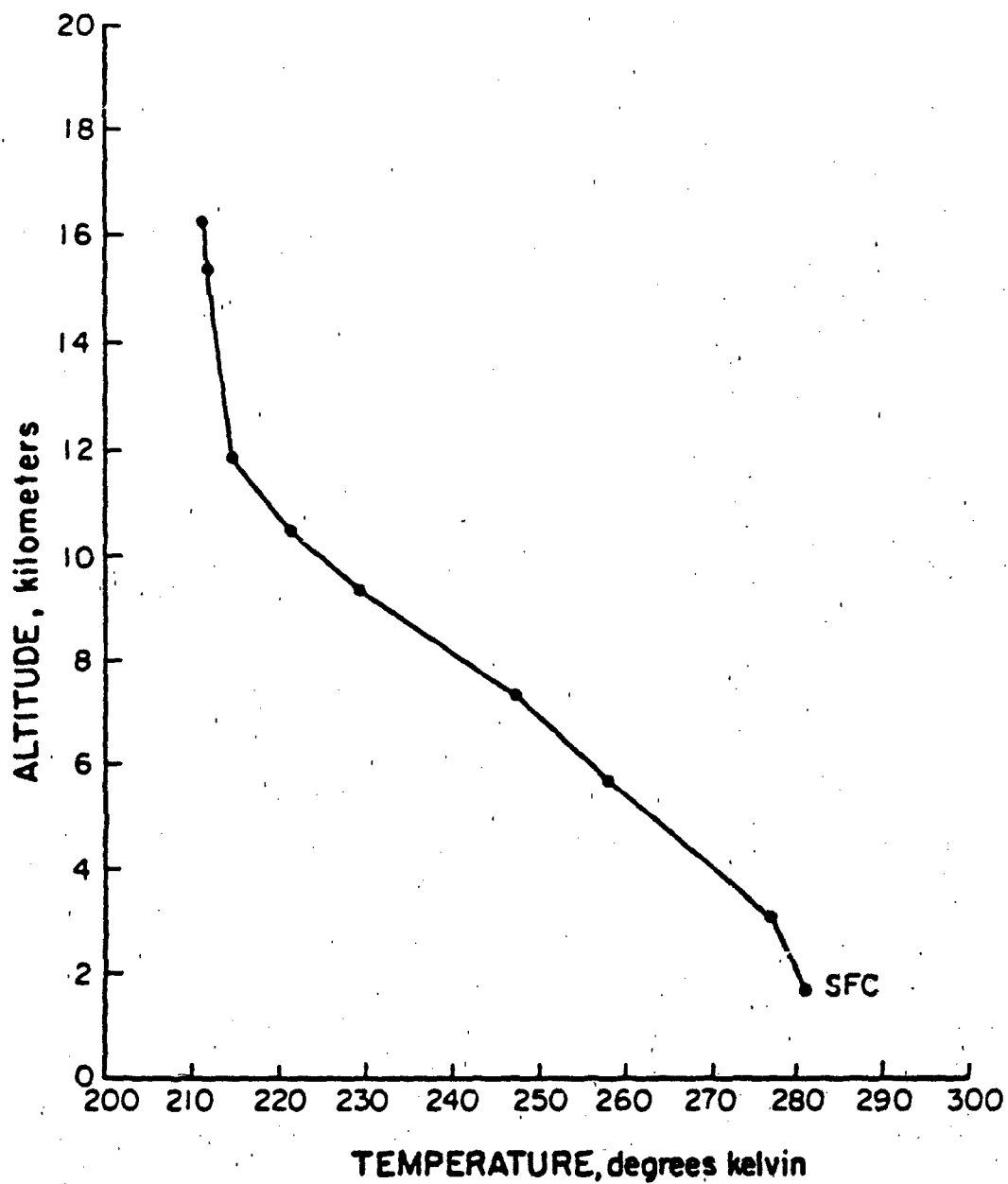Colorado, 1200 GMT, 31 October 84.

Figure 6-5
Temperature versus height profile for Denver,
Colorado, 1200 GMT, 31 October 84 after inversion
has been eliminated.

After the sounding is processed, INTCLD creates a table which contains an entry for each temperature interval in the sounding. Each entry in the table contains: the temperature (T_B) at the bottom of the layer, the temperature (T_T) at the top of the layer, the height (H_B) at the bottom of the layer, and the lapse rate for the entire layer. Table 6-2 shows the table created from the sounding data shown in Figure 6-5. INTCLD uses data in this table to calculate cloud top heights. For each temperature associated with a cloudy pixel, INTCLD finds the interval where the temperature falls. Using the lapse rate for this layer, INTCLD interpolates the height difference from the bottom of the layer. This height difference is added to the height (H_B) at the bottom of the layer. The resulting height is assumed to be the cloud top height for the cloudy pixel. Cloud top heights are calculated for all cloudy pixels in the reduced infrared image.

After all cloud top heights are calculated, the minimum cloud top height is calculated. This minimum cloud top height is assumed to be the maximum allowable cloud base height for all the clouds within the reduced infrared image. This height is displayed on the user terminal and the user determines a reasonable base height for the clouds in the sub-area. This value is entered into the program. As long as the value is below the maximum allowable base height it is accepted by INTCLD.

Finally, after the cloud base height is entered, INTCLD creates three cloud layer files. These files contain data which define cloud cover and contain a cloud top height and cloud base height for each

Table 6-2
Interval table produced from temperature
versus height profile shown in Figure 6-5.

LEVEL	TEMPERATURE (T_B)°K	TEMPERATURE(T_T)°K	LAPSE RATE °K/km	HEIGHT (H_B) km
1	281.6	276.7	-3.60	1.65
2	276.7	258.0	-7.11	3.01
3	258.0	246.8	-6.75	5.64
4	246.8	229.4	-8.70	7.30
5	229.4	220.6	-7.33	9.30
6	220.6	214.2	-4.51	10.50
7	214.2	211.2	-.87	11.92
8	211.2	210.2	-1.20	15.37

cloudy pixel in the infrared image. Information contained in these cloud layer files is later used to create 3-D cloud representations that will be displayed above the topographic base.

D.   3-D Topography Models

At this point, a 3-D topography model is created using data contained in the Mercator topographic image. This model mathematically defines the base for the 3-D cloud-topography model and is created using the TOPGEN program.

The process of generating a 3-D topography model begins by reading the data contained within a sub-area of the Mercator topographic image. To find the location of this sub-area, TOPGEN reads the file which was created by the DEFINE program. This file contains a reduction factor and the parameters which define the sub-area. Next, each pixel value contained within the defined sub-area is read and converted to an elevation using the scale factor that was calculated when the topographic image was created. If a reduction factor greater than one was specified, the elevations contained within the sub-area are averaged. The final result is that a 16 x 16, 32 x 32, or 64 x 64 array of elevations is created representing the topography for the specified sub-area.

To define the topography model, elevation data contained in the above array must be scaled horizontally and vertically. Horizontal scaling involves transforming the location of each elevation in the array to a model X and Y coordinate. Vertical scaling involves transforming each elevation in the array to a model Z coordinate. Model X

and Y coordinates are calculated as follows: One is subtracted from each absolute array location and mutiplied by a resolution factor. Thus, a resolution factor of 4 would scale a 32 x 32 array of elevations from 0 to 124 in each direction. The elevation in the southwest corner of the sub-area would have an X and Y coordinate corresponding to (0, 0). The next elevation to the east would have an X and Y coordinate corresponding to (4, 0) while the first elevation to the north would have an X and Y coordinate corresponding to (0, 4) etc. After model X and Y coordinates are calculated, the <u>actual</u> distances respresented by each side of the model are calculated. North-south and east-west distances are averaged and this average distance is divided by the number of units along one side of the model. The result is a model scale factor which specifies the number of meters represented by one model unit. Model Z coordinates are calculated by dividing each elevation in the array by the model scale factor. After all the model Z coordinates are calculated, the resulting model X, Y, and Z coordinates are stored in a coordinate array.

Each model X, Y, and Z coordinate is referred to as a node. To complete the description of the topography model, the exact sequence for connecting each node is specified. This sequence is stored in a connectivity array. The result is that the topographic surface is defined by a series of four sided polygons.

Usually, the horizontal distance represented by a model is much larger than the vertical distance. As a result, a scale model would appear very flat. To bring out topographic features, a vertical scale

factor can be specified. This vertical scale factor is used to exaggerate the model's vertical scale. To aid the selection of a vertical scale factor, TOPGEN calculates a model height to width ratio and displays this ratio on the user terminal. If the user decides to exaggerate the vertical scale, a vertical scale factor is entered. Then, a new model height to width ratio is calculated and displayed. If the new ratio is not satisfactory, a new scale factor can be entered. After the desired height to width ratio is obtained, each model Z coordinate in the coordinate array is multiplied by this factor.

Finally, a model base is added to give the surface a solid appearance and a parts array is specified. The resulting coordinate array, connectivity array, and parts array is written to a geometry file. This file contains the complete mathematical description for the 3-D topography model. The file is written in a MOVIE.BYU readable format and can be displayed using the DISPLAY program. Another file is also written which contains scaling data used to create the model. Data in this file will be used later to scale 3-D cloud models.

The 3-D topography model can be viewed on the COMTAL monitor using the DISPLAY program. Figure 6-6 shows a topography model as it appears on the COMTAL monitor. The model is displayed as a continuous tone image superimposed with a graphic which contains model contour lines. No rotations have been applied and the resulting view of the model is from the top of the model. This model represents the topography for the entire area shown in Figure 5-1. The vertical scale has been exaggerated by a factor of 15; however, with this view,

Figure 6-6
Top view of 3-D topography model.
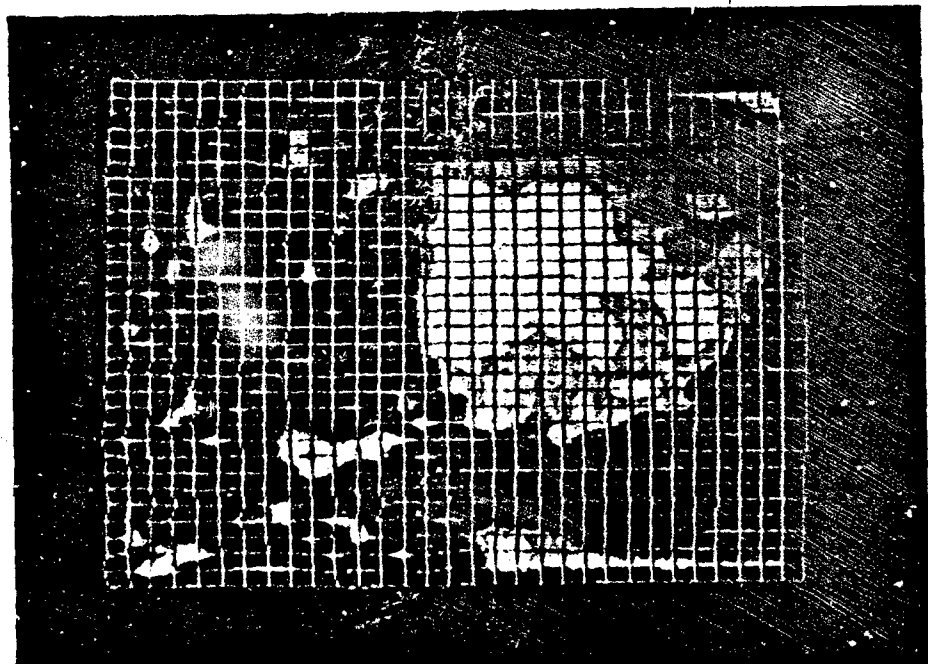
topographic features are not readily noticable. Normally, the 3-D
topography model is not displayed and is done here for illustrative
purposes.

E. 3-D Cloud Models

The previous section explained how the topographic base is
created for the 3-D cloud-topography model. This section explains how
the cloud representations are created.

The cloud representations are created using the CLDGEN program.
CLDGEN begins by reading the cloud layer files which were produced by
the INTCLD program. After a file is read, a "cloud" is extracted from
the cloud layer file. Here, a "cloud" is defined as a group of cloudy
pixels which touch each other in either the east-west direction or
north-south direction. Information defining a cloud is transformed
into X, Y, and Z coordinates using scaling information which was pro-
duced by TOPGEN. Further data manipulation produces a coordinate
array, connectivity array, and parts array. These arrays, which
mathematically define a cloud, are written to a geometry file. This
process continues until all clouds have been extracted from the cloud
layer file. After a cloud layer file is depleted of clouds, the
second and third cloud layer files are processed in the same manner.
Final output for this process is a series of up to 26 geometry files
each of which contains a single 3-D cloud model.

The 3-D cloud models which were produced for the data shown in
Figure 6-3 can be viewed on the COMTAL monitor using the DISPLAY
program. Figure 6-7 shows the 3-D cloud models as they appear on the

Figure 6-7
Top ew of 3-D cloud models for 2132 GMT,
31 October 84
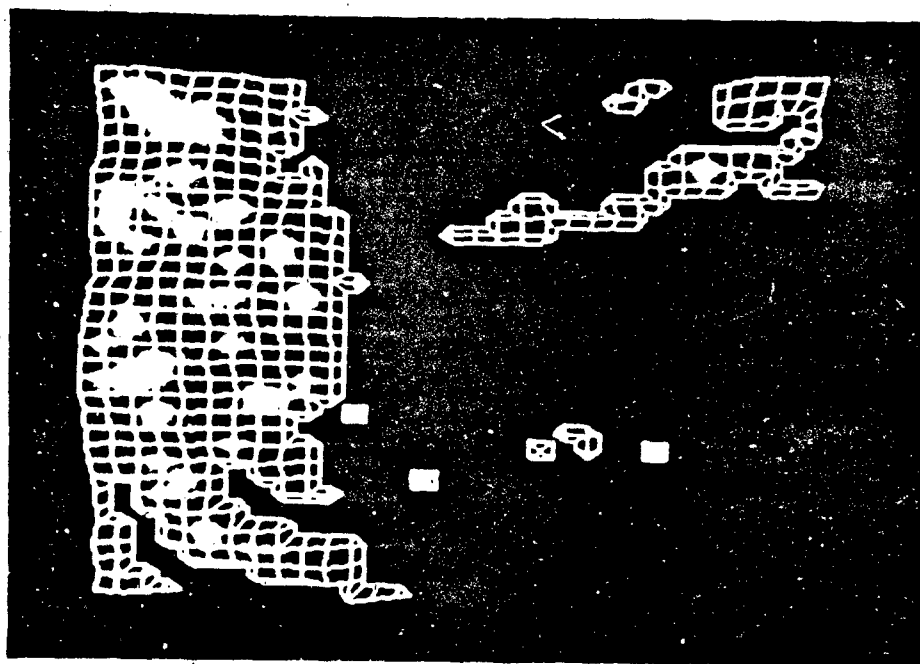
COMTAL. These models have been displayed as a pseudocolor image overlaid by a graphic which contains model contour lines. Again, no rotations have been applied and the resulting view is from the top of the model. The vertical scale is exaggerated by a factor of 15. This figure depicts the cloud cover over the entire region shown in Figure 6-1. Notice the similarity between Figure 6-7 and Figure 6-3. Again, these 3-D models are not normally displayed and are shown here for illustrative purposes.

F.   3-D Cloud-Topography Models

The final step in the process is to combine the 3-D topography model with the 3-D cloud models to produce the 3-D cloud-topography model. Geometry files containing these models are combined using the MERGER program. Final ouput from this program is a geometry file which contains the 3-D cloud-topography model.

The 3-D cloud-topography model, which was produced by combining the cloud models shown in Figure 6-7 and the topography model shown in Figure 6-6, can be viewed on the COMTAL monitor using the DISPLAY program. Figure 6-8 shows the 3-D cloud-topography model as it appears on the COMTAL. Again, no rotations have been applied. Figure 6-8 graphically illustrates how the topograpny model (Figure 6-6) and the cloud models (Figure 6-7) are combined. Figure 6-8 represents the topography and cloud cover for the areas covered by Figures 5-1 and 6-1, respectively.

Figure 6-9 is the same cloud-topography model as shown in Figure 6-8 after rotations have been applied. The resulting view is from

Figure 6-8
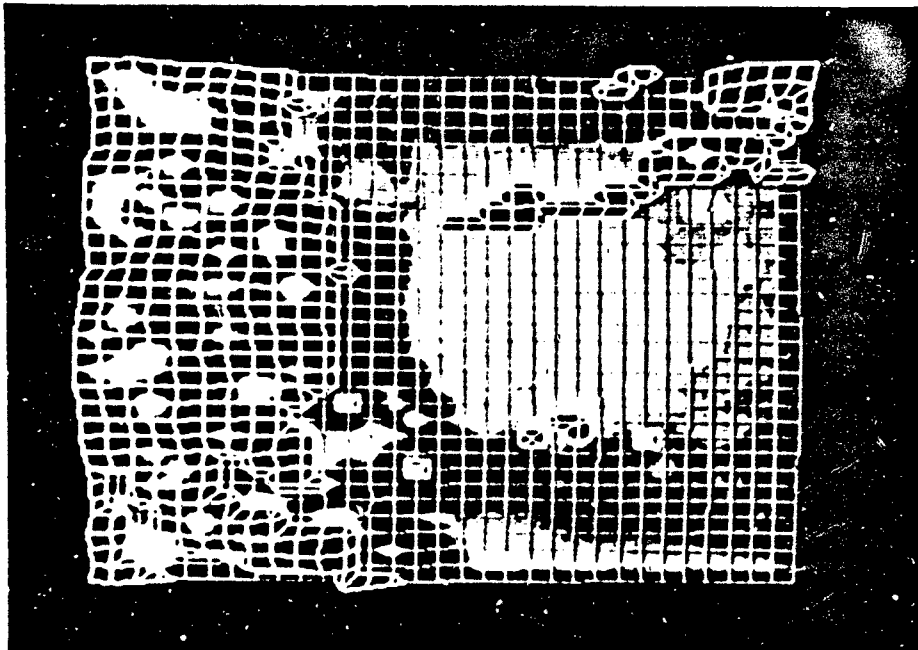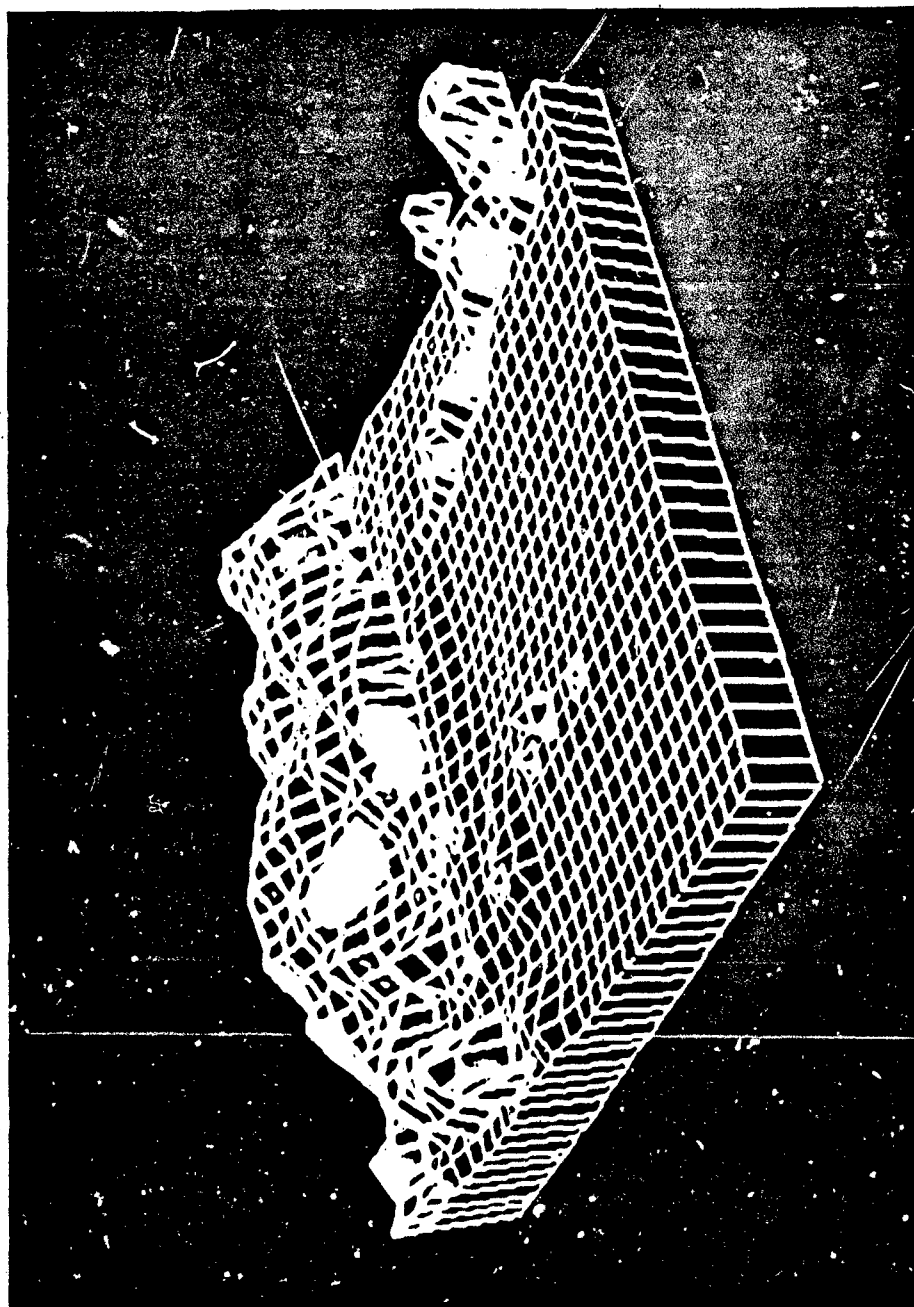Top view of 3-D cloud-topography model for 2132
GMT, 31 October 84.

Figure 6-9
Rotated view of 3-D cloud-topography model for
2132 GMT, 31 October 84.

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the southeast looking northwest. A portion of the Rocky Mountains is visible on the upper left hand side of the model. This view shows the vertical structure of both the terrain and the clouds.

CHAPTER 7

Applications

The aim of the previous four chapters was to explain data, resources, software, and methodology used to create the 3-D cloud-topography model. This chapter illustrates how the 3-D model can be used for cloud studies, briefing aids, and flight simulations.

A. Cloud Studies

GOES satellite data, displayed as digital imagery, is represented by a regularly spaced array of pixels. Each pixel in the array is assigned a specific grey shade based on the numerical value of the pixel. The resulting picture or image is flat scene representation that varies to grey shade from pixel to pixel. Satellite data which is displayed in this manner is commonly used by meteorologists to study vertical cloud structure and cloud development.

To study vertical cloud structure, infrared images are often enhanced. Image enhancement involves altering the image in some way to facilitate the interpretation of its information content. One method of image enhancement involves increasing or decreasing contrast over a range of pixel values. Using this method, enhancement curves are defined which assign lighter or darker grey shades to specified

pixel values. Another method of image enhancement involves the use of color to show detail in the imagery. Using this method, pseudocolor enhancement curves are defined which assign mixtures of the three primary colors (red, green, and blue) to specified pixel values. Both methods are used effectively to show vertical cloud structure.

A time series of satellite images is often used to study cloud development. Normally, a time series consists of two or more satellite images separated by a time step ranging from minutes to hours. Cloud development can be studied by comparing these images in the time series and observing changes in the cloud field. Alternatively, cloud development can be studied by creating a movie loop from the time series of satellite images. Here, satellite images are displayed in rapid succession on an image processing system. The result is a time lapse display of clouds and weather systems which produces the illusion of continuous cloud growth.

The same concepts can be applied using the 3-D cloud-topography model. Displays are produced from the cloud-topography model using MOVIE.BYU software. These displays can be used to study vertical cloud structure and cloud development in a similar fashion to those methods discussed for 2-D satellite imagery.

Three-dimensional cloud-topography models can be used to study vertical cloud structure. To bring out detail, the model's vertical scale is exaggerated. Vertical model scaling is similar to image enhancement in the sense that it facilitates the interpretation of the model's information content. By exaggerating the vertical scale, small height differences are amplified allowing relatively minor cloud

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features to be seen. When the model is displayed, these cloud
features can be viewed and studied from virtually any angle or
perspective. In addition, the satellite data is scaled vertically
proportional to actual height rather than to temperature.

Three-dimensional cloud-topography models can be used to study
cloud development. Here, a time series of cloud models is used
instead of a time series of satellite images. The time series of
models can be displayed on the COMTAL monitor using the DISPLAY
program. Cloud development and growth can be studied by comparing the
models. Alternatively, cloud development can be observed by creating
and displaying movie loops using the time series of 3-D models.

Figures 7-1, 7-3, and 7-5 show a time series of GOES infrared
images as they appear on the COMTAL monitor. Individual images are
separated by a time interval of approximately 15 minutes. The series
shows the development of cumulus convective activity in north-central
Kansas from 2215 GMT to 2245 GMT on 21 June 1984. Figures 7-2, 7-4,
and 7-6 show the corresponding 3-D cloud-topography displays for the
boxed sub-area on the 2-D infrared images. The vertical scale has
been exaggerated by a factor of five to show the vertical cloud struc-
ture. Topographic features cannot be seen since the terrain within
the boxed sub-area is relatively flat. However, the displays show a
realistic depiction of a growing cumulus cloud above the corresponding
topography. Figure 7-2 shows initial development. Figure 7-4 shows a
cumulus tower developing out of the cumulus cloud.

Figure 7-1
Mercator infrared image for ?115 GMT, 21 June 84.

Figure 7-2
3-D cloud-topography model for boxed sub-area
in Figure 7-1.

CO. NE
KS

OK

21 JUN 84
2215 GMT

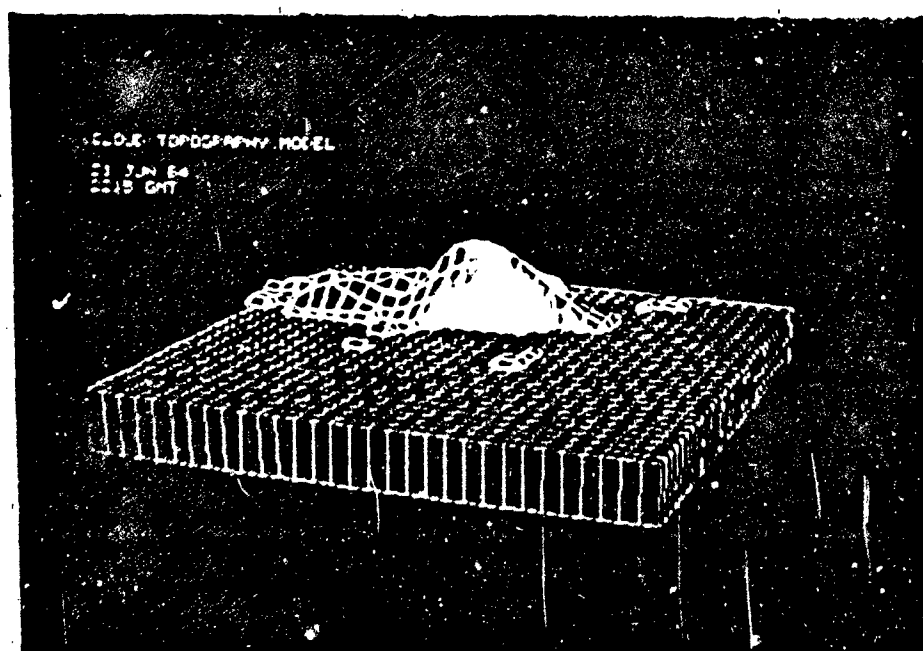C.O.E. TOPOGRAPHY MODEL
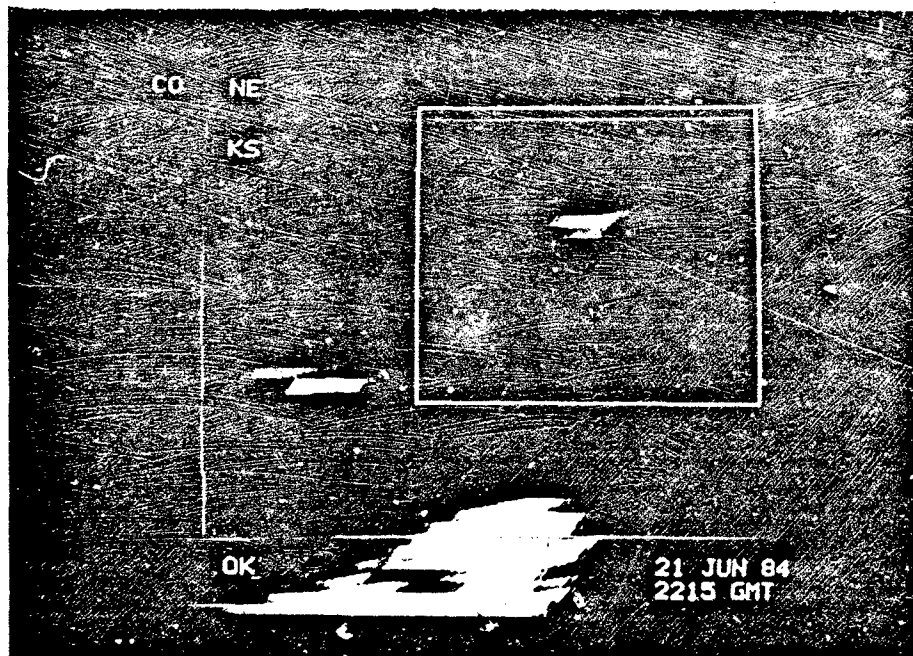21 JUN 84
2215 GMT

Figure 7-3
Mercator infrared image for 2229 GMT, 21 June 84.

Figure 7-4
3-D cloud-topography model for boxed sub-area
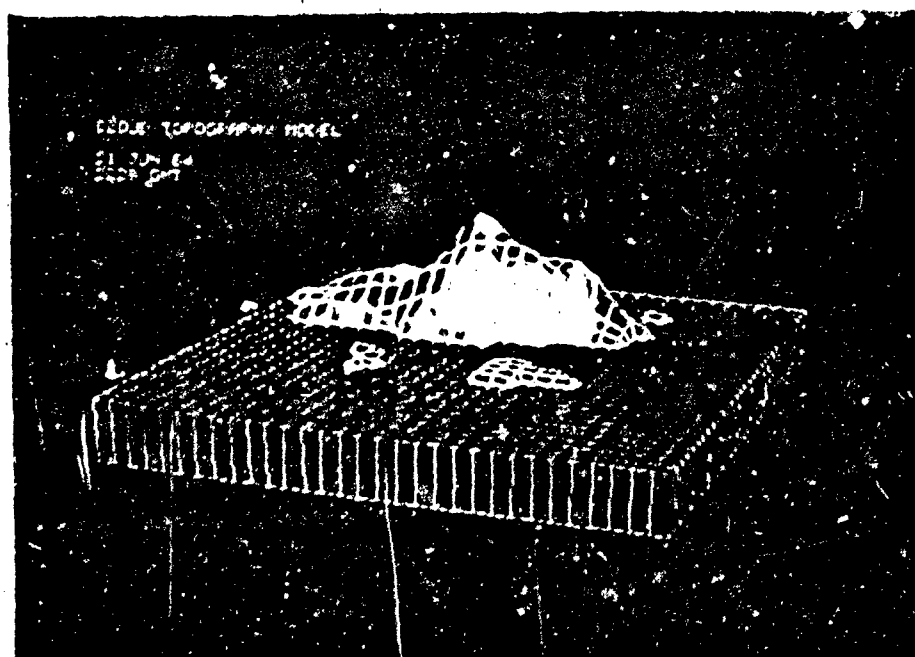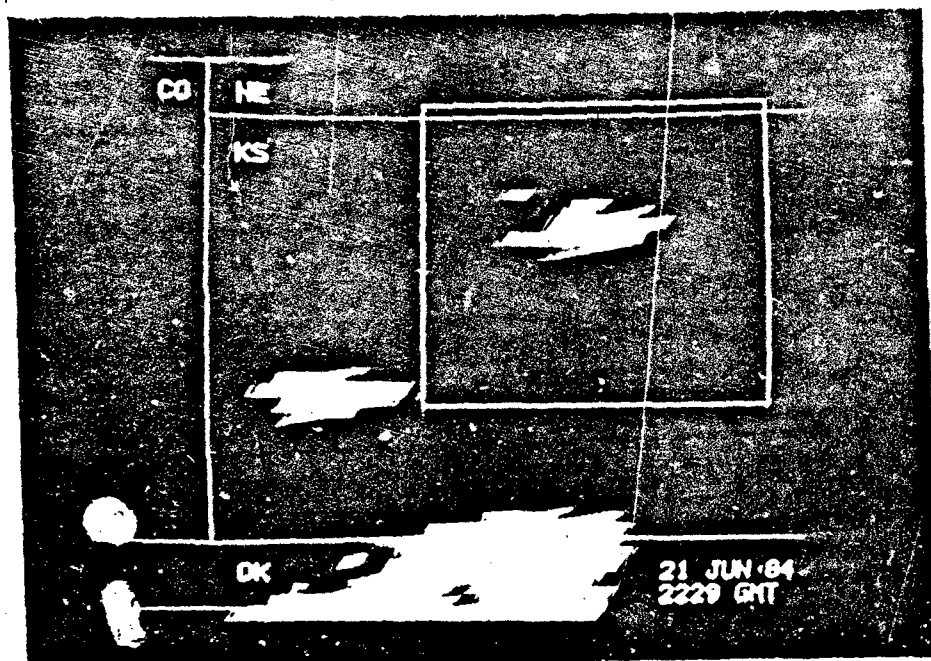in Figure 7-3.

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CEDAR TOPOGRAPHIC MODEL
21 JUN 84
2229 GMT

Figure 7-5
Mercator infrared image for 2245 GMT, 21 June 84.

Figure 7-6
3-D cloud-topography model for boxed sub-area
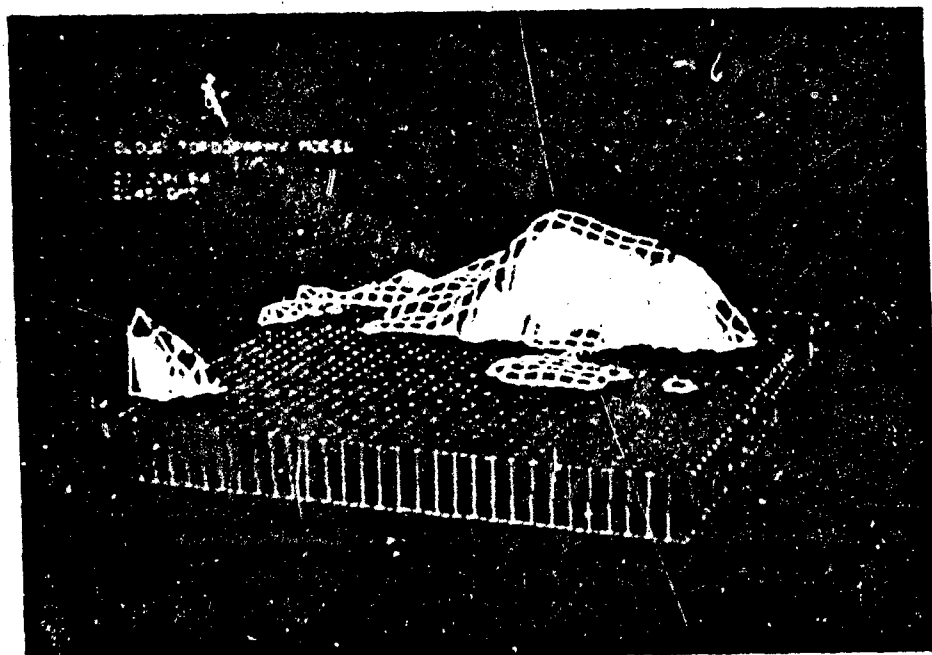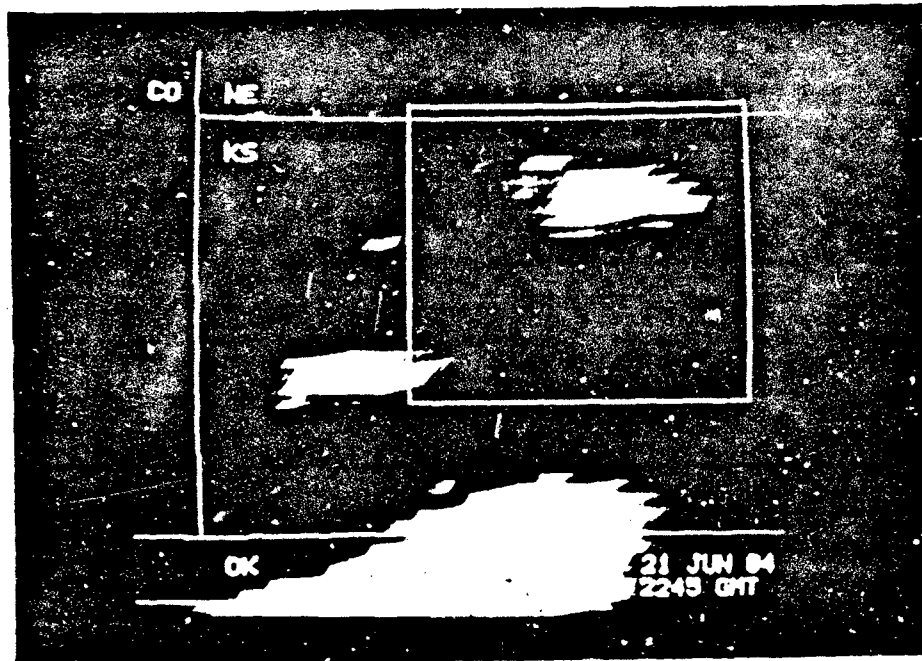in Figure 7-5.

Figure 7-6 shows further development of the cumulus tower and signifi-
cant development to the east. The entire sequence shows the develop-
ment of a small isolated thunderstorm which is propogating to the
east. Clearing is seen behind the storm. Figures 7-2, 7-4, and 7-6
were part of a four frame movie loop which showed this development in
3-D perspective.

In cloud studies, displays similar to those shown in Figures 7-2,
7-4, and 7-6 can be used to study vertical cloud structure and cloud
development. Displays such as these graphically show cloud develop-
ment in a realistic manner. When used in conjunction with 2-D flat
satellite imagery, greater image understanding is realized.

B. Briefing Aids

Displays produced from the 3-D cloud-topography model contain
information on cloud cover and weather systems which is of interest to
pilots. In addition, these displays effectively present satellite
data in such a way that the information can be easily understood and
comprehended. As a result, these displays can be used as an aid to
brief pilots on weather. However, to make the display more meaningful
to a pilot and to enhance the displays information content, flight
tracks can be plotted on the 3-D model. These flight tracks mathema-
tically define, in 3-D, the path of an aircraft from take-off to
landing. When displayed with the 3-D model, flight tracks enable the
pilot to visualize atmospheric conditions along the planned route.

Flight tracks can be plotted on the 3-D cloud-topography model
using the FLTRAK program. FLTRAK accepts five parameters which are

needed to mathematically define the 3-D track. These parameters include the aircraft's take-off location, average ascent angle, average cruising altitude, average descent angle, and landing location. The take-off and landing locations are specified by entering each locations respective latitude and longitude. Average ascent angle is specified by entering the aircraft's climb angle from the point of take-off to the point where the aircraft reaches its cruising altitude. Similarly, average descent angle is specified by entering the aircraft's descent angle from the point where the aircraft departs from cruising altitude to the point where the aircraft lands. Cruising altitude is specified by entering the aircraft's average altitude, between ascent and descent, in meters. Once all parameters are entered, FLTRAK uses this data to scale a model part defining the aircraft's flight path. This model part is then merged to the specified 3-D cloud-topography model.

Figure 7-7 shows a Mercator infrared image for 21.32 GMT, 31 October 84. This figure shows the cloud cover for a portion of southern Colorado and northern New Mexico. A line is shown depicting a flight path from Pueblo, Colorado (PUB) to Durango, Colorado (DRO). Figure 7-8 shows that this route crosses two mountain ranges, the Sangre de Cristo Mountains to the east and the San Juan Mountains to the west. These two ranges are separated by the relatively flat San Luis Valley. Figure 7-7 shows orographically induced clouds formed over these two mountain ranges.

Figure 7-9 shows the corresponding cloud-topography display for the data shown in Figures 7-7 and 7-8. In this figure, the 3-D

Figure 7-7
Mercator infrared image for 3132 GMT, 31 October 84
with flight path plotted.

Figure 7-8
Mercator topographic image with flight
path plotted.

Figure 7-9
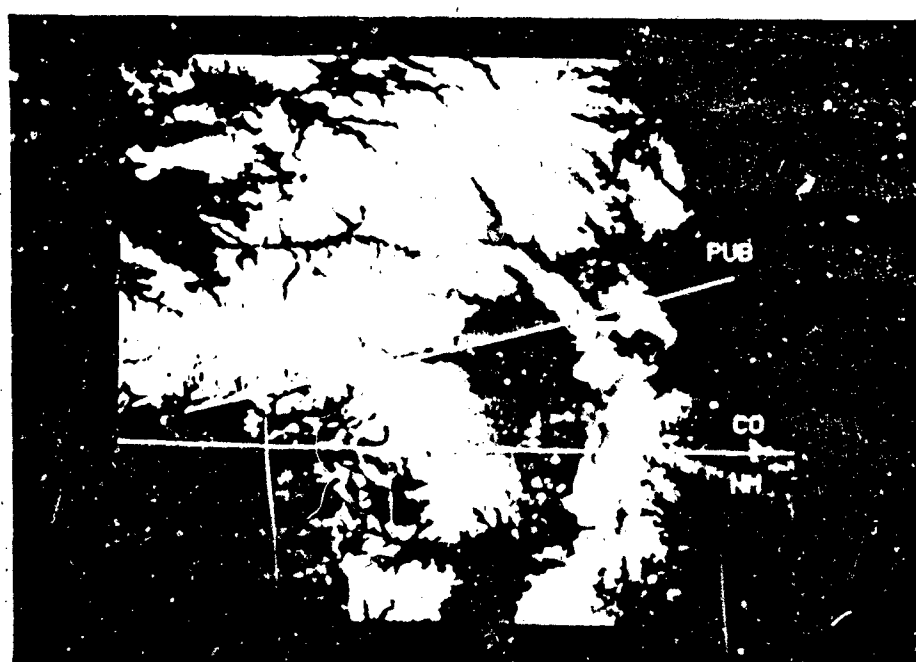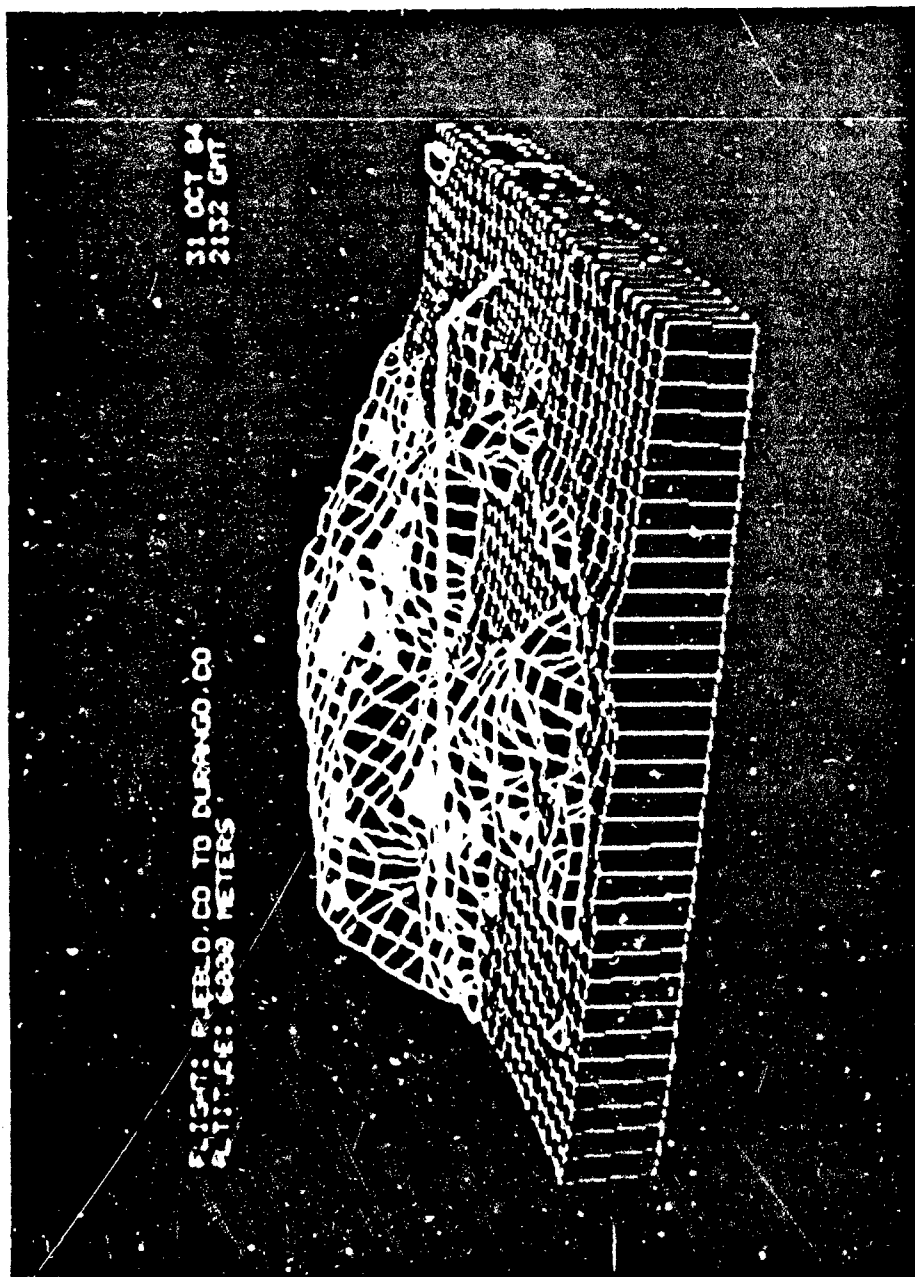3-D cloud-topography model for data shown in
Figures 7-7 and 7-8 with flight track plotted.

FLIGHT: PUEBLO, CO TO DURANGO, CO
ALTITUDE: 6000 METERS

31 OCT 84
2132 GMT

cloud-topography model is viewed from the southeast. A flight track

is shown depicting the route from Pueblo, Colorado to Durango,

Colorado. The track has been defined by a cruising altitude of 6000

meters and ascent and descent angles of 8 degrees. In this display,

ascent and descent angles appear greater than 8 degrees because the

vertical scale of the 3-D cloud-topography model has been exaggerated

by a factor of 10. From Figure 7-9, it is obvious that a pilot flying

this route would encounter orographically induced clouds over the

mountain ranges. However, at an altitude of 6000 meters, the pilot

should be flying well above the cloud tops. In addition, the display

shows that the pilot could expect clear conditions for take-off and

landing. Clear skies could also be expected over the San Luis Valley.

As a briefing aid, displays similar to Figure 7-9 could be shown

to pilots to brief them on weather. In this type of display,

topography data and satellite data are presented in such a way that

the information can be quickly and effectively comprehended. Data

presented in this manner lets the pilot visualize conditions along the

intended route.

C.   Flight Simulations

An alternate way of presenting cloud and topography data is

from the same perspective that a pilot might see the actual clouds and

topography. This display method uses MOVIE.BYU software to manipulate

and display the 3-D model in such a way that simulates flight.

Figure 7-10 shows a Mercator visible image valid for 2132 GMT, 31

October 84. This image covers the same geographical area shown in

Figures 7-7 and 7-8. Data is also valid for the same time period. A line defining the flight path from Pueblo, Colorado to Durango, Colorado is also shown in Figure 7-10 A box drawn in the center of the image defines a sub-area that is to be transformed into a 3-D cloud-topography model. Inside the boxed-off area, two bands of orographically induced clouds can be seen which have formed over the Sangre de Cristo Mountains to the east and San Juan Mountains to the west.

The 3-D cloud-topography model created for the sub-area in Figure 7-10 is shown in Figure 7-11. Figure 7-11 graphically shows the view the pilot would see while flying at an altitude of 6000 meters (MSL) and looking west along the line shown in Figure 7-10. This view is valid for point A (labeled in Figure 7-10). In Figure 7-11, a portion of the Sangre de Cristo Mountains is seen in the foreground and the first band of clouds formed above these mountains is visible. Off in the distance, a portion of the cloud free San Luis Valley is seen. On the horizon, the second band of clouds which are formed over the San Juan Mountains is visible.

Figure 7-12 shows the view the pilot might see at point B (labeled in Figure 7-10). In the foreground, cloud tops are visible. More of the San Luis Valley is visible and the orographic clouds on the horizon appear a bit closer.

Figure 7-13 shows the view the pilot might see at point C (labeled in Figure 7-10). Here, the first band of clouds is no longer visible. The cloud free San Luis Valley is seen in the foreground and the second band of clouds is seen on the horizon.

Figure 7-10
Mercator visible image for 2132 GMT, 31 October 84
with flight path plotted.

Figure 7-11
View of 3-D cloud-topography model for boxed
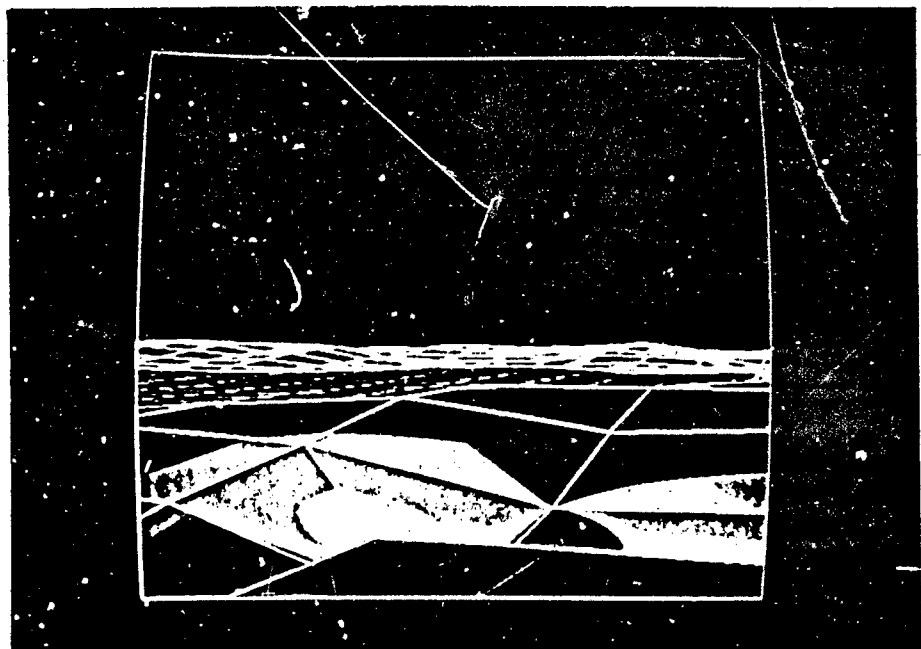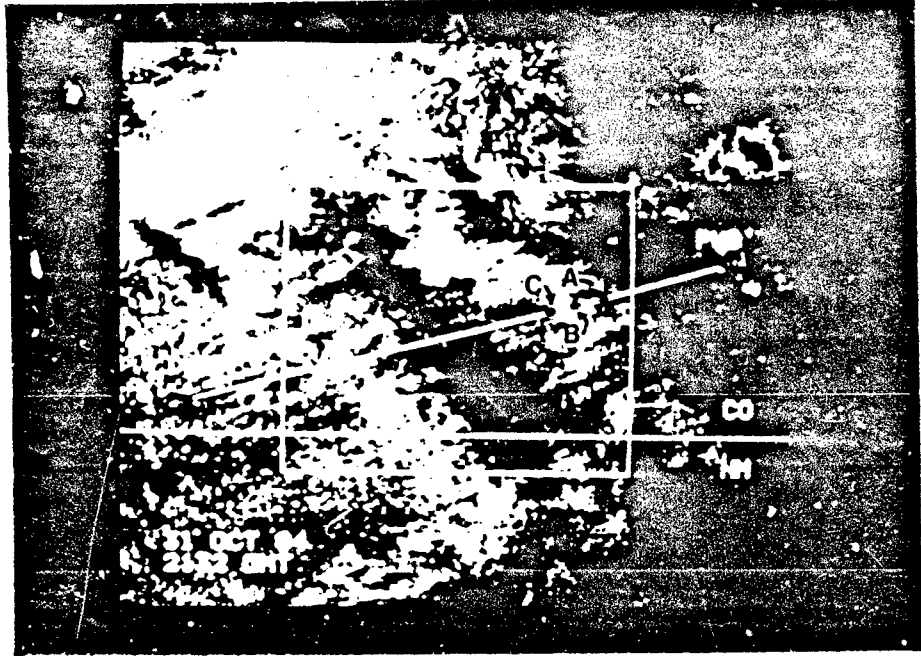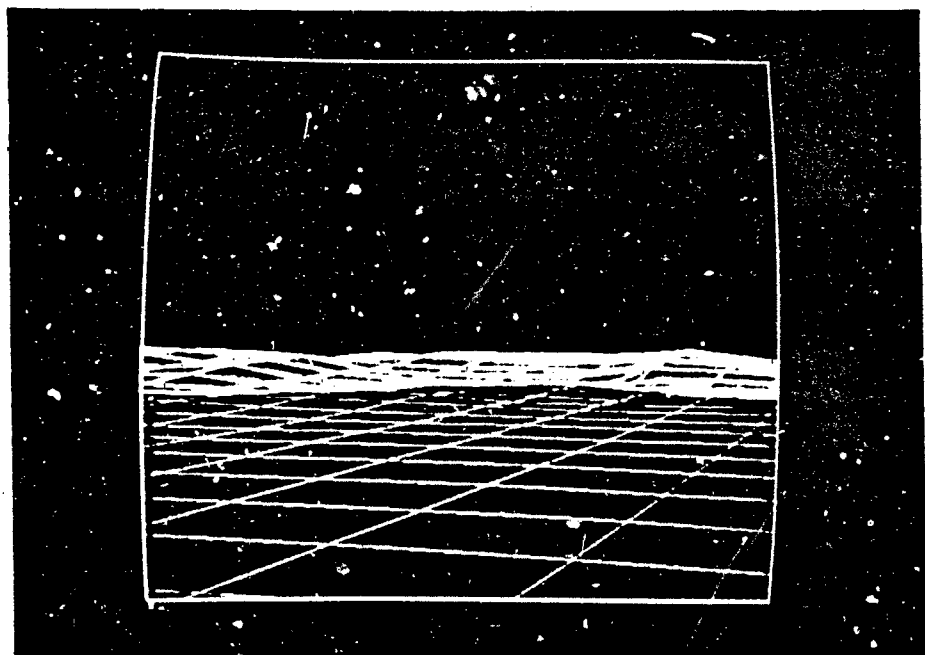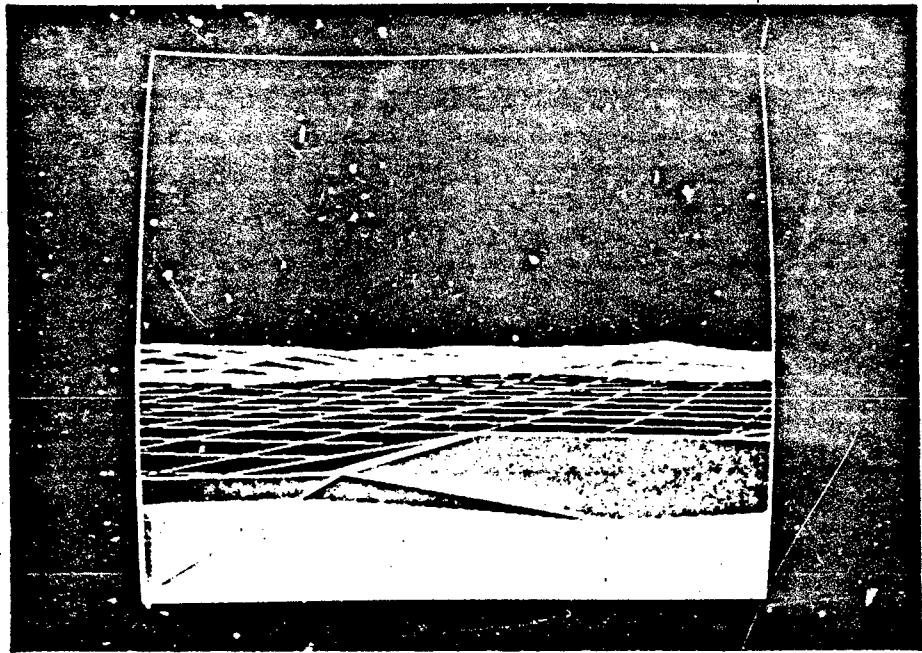sub-area in Figure 7-10 at point A.

Figure 7-12
View of 3-D cloud-topography model for boxed
sub-area in Figure 7-10 at point B.

Figure 7-13
View of 3-D cloud-topography model for boxed
sub-area in Figure 7-10 at point C.

The sequence (Figures 7-11, 7-12, and 7-13) graphically shows what a pilot might see at several points along the hypothetical flight path. It must be emphasized that these displays are created using actual satellite data versus simulated data. Data displayed in this way, or perhaps movie loops showing such a sequence, could be shown to pilots to inform them on weather conditions along a flight route.

The next sequence of figures compares an actual photograph of clouds to a computer graphic display of clouds. The photograph was taken from a commerical airliner on approach to Stapleton International Airport in Denver, Colorado on 2 December 84. The computer graphic display of cloud cover is valid for 2132 GMT, 31 October 84 for the area shown in Figure 6-1. It is important to note that the valid times of the graphic display and the photograph do not match. However, the meteorological situation is similar in that orographically induced clouds are formed over the Front Range of the Rocky Mountains.

Figure 7-14 shows a scale model of the cloud cover and topography shown in Figures 6-1 and 5-1. The area covered by this model includes most of central Colorado including the Denver area and the Front Range.

Figure 7-15 shows a view of the above cloud-topography model from the same perspective a pilot might see clouds and topography on an approach to Stapleton International Airport. This view shows the orographically induced clouds over the Front Range.

Figure 7-16 is a photograph of orographically induced cloud cover over the Front Range. This photograph was taken looking west and slightly north, approximately 100 kilometers from the Front Range using a 28 millimeter, wide angle lens.

Figure 7-14.
3-D cloud-topography model for 2132 GMT, 31 October 84
drawn to scale.
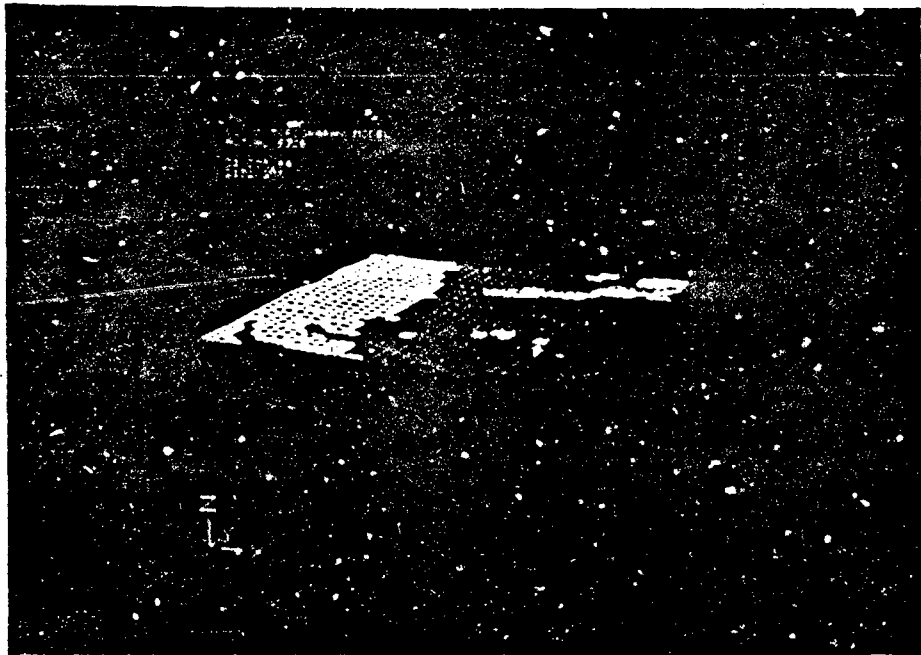
Figure 7-15
3-D cloud-topography model for 2132 GMT, 31 October
84, showing orographically induced clouds over
the Front Range.

Figure 7-16
Photograph of orographically induced clouds over
the Front Range taken from a commerical airliner on
2 December 84.
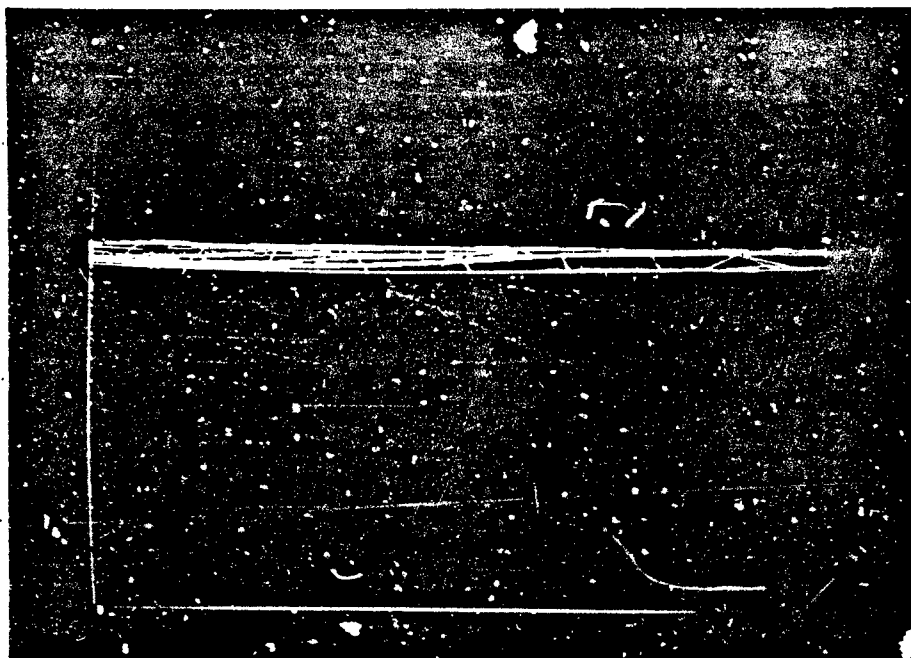
By comparing Figures 7-15 and 7-16, the graphic representation of the orographic clouds is similar to the actual photograph of the orographic clouds. This last sequence of figures shows that graphically produced cloud representations can be used for flight simulations.

CHAPTER 8

Conclusion

A. Summary

In this research, GOES satellite data and topography data
have been mapped into high resolution, Mercator images which accura-
tely overlay each other. As a result, cloud cover information can be
obtained with respect to topography. Using a matching set of Mercator
images, a sub-area can be specified which defines the portion of the
images to be transformed into a 3-D, mathematically defined model. To
determine cloud cover for this sub-area, a cloud/no cloud threshold is
specified for the infrared image. Pixels with radiance counts greater
than or equal to the cloud/no cloud threshold are considered cloudy.
Cloud top heights are determined for cloudy pixels by relating the
pixels radiance count to temperature. The resulting temperatures are
then related to height using an atmospheric profile of temperature
versus height. Cloud base heights are determined for cloudy pixels by
manually estimating the base height. This estimation is based partly
on guidance from data contained in the infrared image and partly on
meteorological experience. Information contained in the Mercator
topographic image is used to produce a 3-D topography model for the
defined sub-area. Cloud top height information, cloud base height

information, and cloud cover information is used to produce 3-D cloud models for the defined sub-area. The resulting 3-D topography model and the 3-D cloud models are combined to produce the 3-D cloud-topography model.

Three-dimensional cloud-topography models can be rotated, manipulated, illuminated, and displayed using MOVIE.BYU software. The resulting displays produce a realistic depiction of cloud cover above a topographic surface. Due to the display's visual appeal and enhanced information content, these cloud-topography displays are well suited for cloud studies, briefing aids, and flight simulations.

For cloud studies, 3-D cloud-topography models can be used to study vertical cloud structure and cloud development using methods similar to those currently used for 2-D flat imagery. When used in conjunction with 2-D satellite imagery, the displays produced from the 3-D model enable greater image understanding.

For pilot briefing, 3-D cloud-topography models can be modified to show an aircraft's flight track. As a briefing aid, the displays produced from the modified 3-D model enable the pilot to visualize atmospheric conditions along the planned flight route. When presented in this manner, satellite data and topography data can be quickly and effectively comprehended.

For flight simulation, 3-D cloud-topography models can be rotated and manipulated in such a way that cloud cover and topography can be viewed from the same perspective a pilot might see the actual cloud cover and topography. Data viewed in this manner can also be used to brief pilots, or could be used in flight simulations.

B. Future Work

One area for future work would focus on improving the 3-D
cloud-topography model. Currently, the cloud-topogaphy model contains
only one layer of clouds. Although the software is set up to handle
up to three layers, current methods for cloud determination can only
descriminate one layer of clouds in the satellite image. The addition
of the capability to descriminate multiple cloud layers would make the
3-D model more realistic. Another model improvement would incorporate
a quantitative vertical scale into the model. Mackinen (1984) descri-
bes two excellent methods for scaling cloud data which could be
adapted to the 3-D cloud-topography model. The capabililty to display
a quantitative vertical scale would allow the user to better estimate
the vertical extent of clouds. Another model improvement would
incorporate an option to scale the topographic data in such a manner
that would allow topographic features to be seen in areas where
terrain is relatively flat. For example, the cloud-topography
displays shown in Figures 7-2, 7-4, and 7-6 show the development of a
thunderstorm over northern Kansas. However, topographic features in
this area cannot be seen. The incorporation of advanced vertical
scaling techniques would show topographic features without distorting
the clouds which are displayed above the topographic surface. One
final improve.ent would incorporate more advanced techniques to: 1)
descriminate cloudy and clear regions in infrared satellite image, 2)
determine cloud top heights, and 3) determine cloud base heights.
These improvements would increase the accuracy of the data being
displayed.

Another area for future work would focus on decreasing the amount of time required to create and displa/ a 3-D cloud-topography model. Currently, it takes approximately five minutes to create a 3-D model, and fifteen minutes to display the 3-D model. Thus, most of the time is spent displaying the 3-D model. To significantly reduce this time, more efficient algorithms are needed to display the 3-D model. To speed up the process, the general purpose MOVIE.BYU software could be abandoned in favor of new software which is specifically designed for the display of meteorological data. This new software would use more efficient algorithms to perform the coordinate transformations needed to display the model. Another approach to this problem would utilize a hardware/sofware combination to perform these coordinate transformations. This approach could result in systems that perform the coordinate transformation function and the model display function in real time (approximately 1/30 of a second). A real time system would be ideal for applications such as flight simulation where actual movement during flight could be simulated.

Still another interesting area for future work would compare actual photographs of clouds to computer graphic cloud representations produced from the 3-D cloud-topography model. Here, aircraft flights could be made and photographs of clouds could be taken. At the same time the photographs are taken, satellite data could be collected. Computer graphic representations of clouds could be produced from the satellite data and compared to the actual photogaphs taken from the aircraft. Such comparisons would be valuable for cloud studies, model improvements, and other research activities.

One last area for future work would explore additional applications for the 3-D cloud-topography model. Three applications for the 3-D cloud-topography model are discussed in this thesis. Other applications could be developed which would take advantage of the MOVIE.BYU software display capabilities. One possible application would incorporate radar data into the 3-D cloud-topography model. Using this idea, cloud cover and radar echo regions could be displayed to show precipitation areas in clouds. Another possible application would incorporate other meteorological data into the 3-D cloud-topography model. Displays could be produced showing cloud cover and isentropic surfaces, cloud cover and pressure surfaces, or cloud cover and any other meteorological parameter which could be adequately described as a surface. Another possible application would use the 3-D cloud-topography model for spatial cloud studies. Here, 3-D clouds could be projected onto a surface and percent cloud free line of sight could be calculated as a function of angle and distance. These are but a few potential applications which could be developed using the 3-D cloud-topography model. Undoubtedly, there are many more.

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